St3TART-FO
FRM for Sentinel-3 Land Altimetry

St3TART-FOLLOW-ON: FIDUCIAL REFERENCE MEASUREMENTS (FRM) - S3 LAND ALTIMETRY

Inland Waters FRM provision roadmap (TD-08_4), v1.0

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Acronyms

AEM	Airborne ElectroMagnetic
ALS	Airborne Laser Scanner
AO	Announcement of Opportunity
API	Application Programming Interface
AWI	Alfred Wegener Institute
AWS	Automatic Weather Stations
Cal/Val	Calibration/Validation
CCI	Climate Change Initiative
CCR	Contract Close-out Review
CLS	Collecte Localisation Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CO	Contract Officer
CRISTAL	Copernicus polaR Ice and Snow Topography ALtimeter
CS-2	CryoSat-2 mission
CSV	Comma-Separated Values
DOI	Digital Object Identifier
DSM	Digital Surface Models
DTU	Denmark’s Technical University
EASE	Equal Area Scalable Earth
EEA	European Environmental Agency
eLTER	European Long-Term Ecosystem Research
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAQ	Frequently Asked Questions
FF	Fully Focused

FFP	Firm Fixed Price
FO	Follow On
FR	Final Review
FRM	Fiducial Reference Measurement
FRM-CC	FRM Collaborative Campaign
GCOS	Global Climate Observing System
GCP	Ground Control Point
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographic Information System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRDC	Global Runoff Data Center
IMBIE	Ice sheet Mass Balance Intercomparison Exercise
IPS	Ice Profiling Sonar
ITT	Invitation To Tender
KO	Kick Off
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (literally : Laboratory of Space Geophysical and Oceanographic Studies)
LiDAR	Light Detection And Ranging
LOCEAN	Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques (literally : Laboratory of Oceanography and Climate: Experimentations and Numerical Approaches)
MoM	Minutes of Meeting
MPC	Mission Performance Cluster
NetCDF	Network Common Data Form
NORCE	Norwegian Research Center
NSIDC	National Snow and Ice Data Center
NPI	Norwegian Polar Institute
OLCI	Ocean and Land Colour Instrument

ORR	Operation Readiness Review
OZCAR	Observatoires de la Zone Critique, Applications et Recherches (literally: Critical Zone Observatories, Applications and Research)
PM	Progress Meeting
POCA	Point of Closest Approach
PPP	Precise Point Positioning
PR	Progress Review
PVR	Product Validation Report
QA4EO	Quality Assurance framework for Earth Observation
QGIS	Quantum Geographic Information System
QWG	Quality Working Group
RB	Requirements Baseline
REMA	Reference Elevation Model of Antarctica
S3	Sentinel-3
S3VT	Sentinel-3 Validation Team
SAR	Synthetic Aperture Radar
SBLA	Single Point Laser Altimeter
ScalSIT	Super Cal/Val Site Identifier Tool
SfM	Structure-from-Motion
SI	Système International d'unités (literally: International System of Units)
SIMS	Sea Ice Measurement System
SIN'XS	Sea Ice thickness product intercomparison exercise
SLSTR	Sea and Land Surface Temperature Radiometer
SMB	Surface Mass Balance
SNO-GLACIOCLIM	Service National d'Observation GLACIOlogique et CLIMatologique des régions de montagne (literally: National Glaciological and Climatological Observation Service for Mountain Regions)
SoW	Statement of Work
SPR	Set-up Phase Review
SWOT	Surface Water and Ocean Topography

St3TART	Sentinel-3 Topography mission Assessment through Reference Techniques (contract between 2021 and 2023)
St3TART-FO	St3TART Follow-On
STM	Surface Topography Mission
TBD	To Be Defined
TDP	Thematic Data Products
TO	Technical Officer
UAV	Unmanned Aerial Vehicles
UN	UNfocused
WP	Work Package

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[RD3]	NOV-FE-1464-NT-017	TD-01: FRM Super Site Operational Plan
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1. Introduction

1.1. Purpose and scope

This document presents the Inland Waters FRM Provision Roadmap, originally developed for the St3TART project (2021–2023) and updated in this St3TART-FO project.

In the context of St3TART-FO, this roadmap forms the foundation of the follow-on activities, which aim to establish an operational framework for FRM provision to support validation activities and foster the exploitation of the Sentinel-3 SAR altimeter Hydro-Cryo Thematic data products.

The roadmap is intrinsically linked to the operational plans of St3TART-FO, with both components designed to complement and reinforce each other.

For detailed insights into these operational plans, please refer to:

- The FRM Super Site Operational Plan [RD3]
- The FRM Opportunity Site Campaign Operational Plan [RD4]

To ensure continued relevance within St3TART-FO, this roadmap will be reviewed and updated as necessary.

1.2. Overview of this document

In addition to this Introduction chapter, this Roadmap for S3 STM Land FRM operational provision includes the following chapters:

- Strategy for Operational FRM provision over inland water
- Cal/Val super sites over rivers
- Cal/Val super sites over lakes
- Existing in-situ sensor networks for Opportunity Cal/Val sites
- Metrological uncertainty analysis for inland FRM

In [RD7] it has been demonstrated that each virtual station site over inland water bodies has specific characteristics, especially concerning the impact of the natural excursion of the satellite track due to the current orbit control constraints, the local water topography and roughness and their temporal variation, which are different for each site. This is particularly true over rivers but is also applicable to lakes to some extent.

The roadmap proposed in this document aims at describing an implementation of a sustainable operational FRM provisioning over inland water with a specific focus on the FRM quality (meeting FRM requirements), the operational production of these reference measurements and the strong will to federate the Cal/Val community to create an emulation around the provision and use of these FRMs.

That is why this roadmap proposes Cal/Val “super sites” that are given in this project as demonstrators that can be duplicated on other sites, thanks to a recipe described in the following chapters. This recipe will cover the different aspects, from the sensor types to use to the strategy to produce FRM. An annual estimate of the running costs of each site will also be made and provided to give a baseline budget for any future open call dedicated to the deployment of new sites. Finally, we also propose to combine this super site approach with the use of existing in-situ networks to involve and federate local partners from different countries.

The strategy we propose in this document is intended to be generic, though with differences between rivers and lakes. However, this strategy is not directly applicable to high-latitude sites. Indeed, lakes and rivers located at high latitudes are of particular interest for Sentinel-3 Cal/Val activities, notably because of the tighter grid of ground tracks allowing for shorter revisit time, however the presence of ice requires specific means and analysis that were not analysed during this project framework. Thus, and in agreement with our proposal, this aspect is not further developed here.

2. Strategy for operational FRM provision over inland water

2.1. MPC requirements for operational Cal/Val activities

S3 LAND STM MPC performs routine as well as in-depth analysis of the quality of the altimetric data over inland waters. Routine activities consist in emitting a Cyclic Performance Report over Inland Waters within 5 days after the end of each cycle. This cyclic report contains absolute comparisons to in-situ data even for STC products. This sets the following requirements on the FRM:

- FRM shall have a **reliable timeliness < 6 days** for **STC products**. For **NTC products**, consolidated FRM shall have a **timeliness of 2 weeks**.
- FRM **shall be georeferenced** to be useful for absolute comparison of water surface heights
- FRM shall consist of **long timeseries** to be able to detect anomalies in the evolution of the in-situ/altimetry data comparison metric (namely RMSE), at least one year to cover a hydrological cycle.

The in-depth analysis performed by MPC covers both rivers and lakes surfaces. Among these activities, the validation of the Full Mission Reprocessing requires having a long in-situ time series covering the life of the mission. In-situ datasets since S3A launch early 2016 are useful to validate the reprocessing campaigns and assess the compliance to the "**consistent, long-term** collection of remotely sensed data, of **uniform quality**" requirement present in S3 MRD [RD31]. MPC therefore supports the policy of 'making existing means to FRM standards.

MPC is also aiming at building the WSH error budget over inland waters on the reconstructed WSH. As presented in [RD7], uncertainty breakdown in between the different contributors, the main contributor to the error budget is the range uncertainty. It has been shown within S3 LAND STM MPC studies that the accuracy of the L2 Thematic Hydrology products can be as good as 5 cm RMSE over flat canals (see Figure 1). Consequently, FRM are needed with better than 5cm accuracy over such favourable cases to quantify the retracking algorithm error budget (bias and noise).

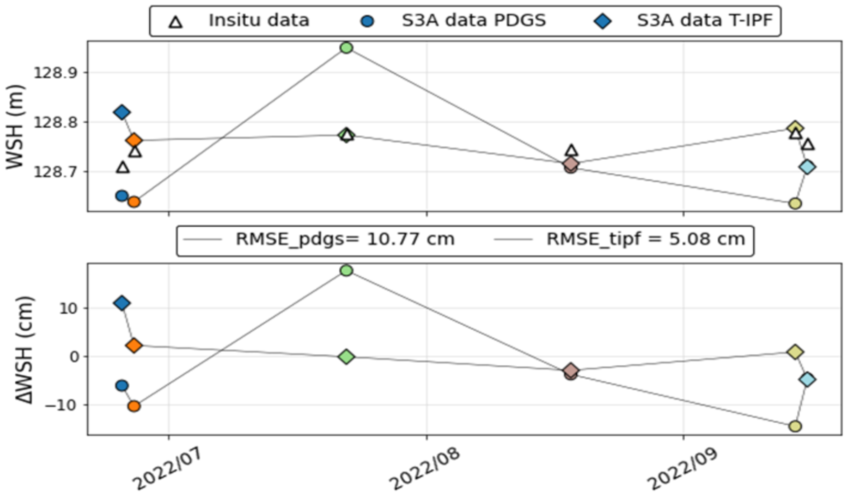


Figure 1: Example of time series of the comparisons of S3A PDGS and S3A Thematic Hydro products with in-situ data over Canal du Midi with Trèbes in Situ data. Top = WSH, Bottom = Difference with respect to in-situ data.

With algorithmic improvements, such as Hamming filtering, associated with the Thematic Hydro products with respect to PDGS Land products, the altimeter better focuses on the SAR band. Impact of the orientation of the water body with respect to the SAR band direction, particularly for rivers due to their elongated shape and their slope, is then expected to have a larger impact. Indeed, the slope of the echogenic surface induces POCA displacement as presented in the Aisne River study case. Figure 2 presents the distribution of the slope at virtual stations positions in two datasets of interest: the median slope at the position of Copernicus Global Land S3A stations is of 35cm/km, such value is expected to induce a 5cm WSH error. In the presence of Hamming filtering, this effect is expected to affect the measurements differently depending on the angle of the river section with the SAR band. MPC recommends that the sites, at least the opportunity sites, present **various geometry configurations** of the water bodies with respect to the SAR band. Having **FRM in increasing complexity** sites is a necessity to understand and provide the error budget.

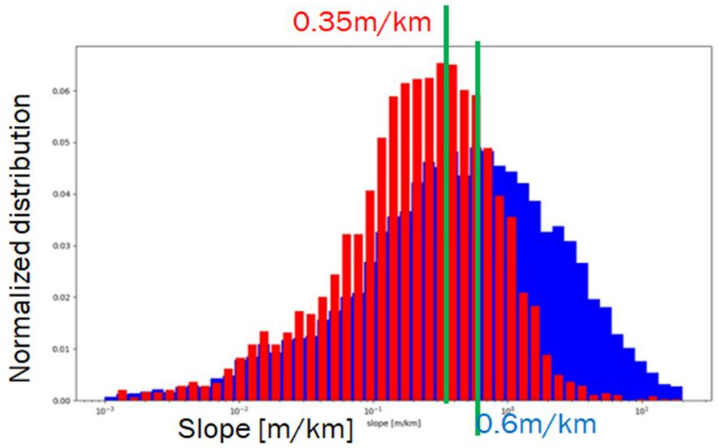


Figure 2: Distribution of the river slope at virtual station (VS) positions in Copernicus Global Land S3A VS dataset (red) and in SWORD database at the positions of S3A theoretical ground track (blue)

Eventually another challenge in valorising altimetry data is being able to disentangle in between the signal of multiple water bodies. MPC activities also aim at validating potential future evolutions of the products, the validation of fully-focus SAR products is among them. It has been shown ([RD15] and [RD16]) that FFSAR waveforms can be contaminated with spurious replicas. A means of better understanding these products over inland waters and validating them would be to **equip**, with in-situ WSH measurement means, **several water bodies that fall within the altimeter footprint** over a few sites. Ideally, considering several sites with various river widths from a few tens of metres to few hundred metres would be of great interest to study the contamination by surrounding echogenic elements, and/or by spurious replicas as a function of water bodies size.

2.2. Recommendations from the CCVS project

The objective of the Copernicus Cal/Val Solution (CCVS, [CCVS | toward a Copernicus Cal/Val Solution]) is to define a holistic solution for all Copernicus Sentinel missions (either operational or planned) to overcome current limitations of Calibration and Validation (Cal/Val) activities. Operational Cal/Val is required to ensure the quality of and build confidence in Copernicus data. However, these activities are currently limited by the following considerations:

- The requirements and objectives need to be revisited to consider new usage of Copernicus products, inter-operability requirements, and to anticipate the needs of future Copernicus missions
- Current Cal/Val activities are constrained by programmatic and budgetary requirements and do not necessarily follow scientific priorities
- Cal/Val activities depend on the operational availability of high-quality Fiducial Reference Measurements (FRM) which are today mostly provided by external entities without strong commitment to the Copernicus program
- Synergies within Copernicus and with other national and international programs are not systematically explored.

To address these limitations CCVS will propose:

- An updated specification of Cal/Val requirements for the Sentinel missions, taking into account inter-operability needs
- An overview of existing Calibration and Validation sources and means
- A gap analysis identifying missing elements and required developments in terms of technologies and instrumentation, Cal/Val methods, instrumented sites and dissemination service.
- A comprehensive Copernicus Cal/Val Solution to organize the long-term provision of FRM for Sentinel missions
- A roadmap documenting how the Cal/Val Solution can be implemented, highlighting responsibility, cost and schedule aspects. This plan will be elaborated in concertation with all stakeholders through four Working

Groups gathering European Space Agencies, Copernicus Services, measurement networks and international partners.

In this framework the report dedicated to satellite altimetry Cal/Val [RD27] demonstrate that in situ FRM is one of the 3 pillars of Cal/Val activities as illustrated in Figure 3.

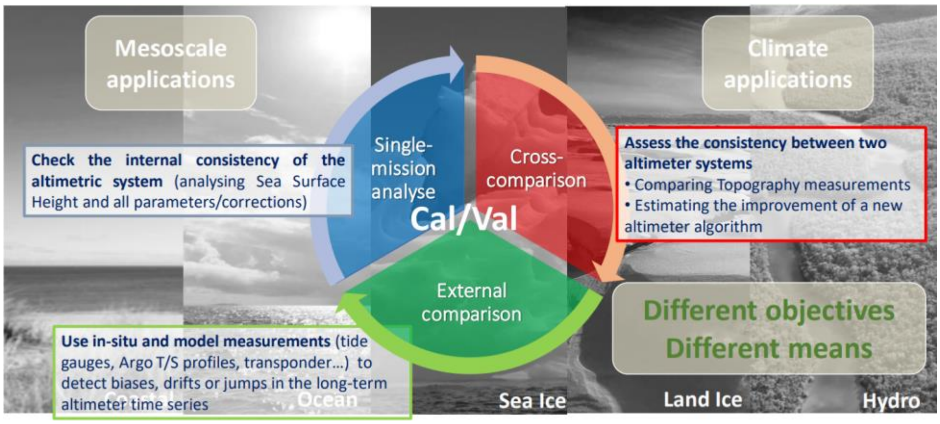


Figure 3: Pillars for altimetry validation activities

This report mentions that for inland waters, the review of the requirements provided in the Cal/Val Plan, proposes to measure the tracking performances (or OLTC precision when operating in Open Loop), the Water Surface Height (WSH) precision and accuracy for different kind of targets (rivers, lakes, estuaries, etc.), of different sizes, compare the results with past and existing missions and finally propose an assessment of other variables such as wind speed, SWH over specific (large) surfaces.

The proposed roadmap is in line with these recommendations to provide Fiducial Reference Measurement of water surface height on different kind of targets and of different sizes for the performance analysis of the Sentinel-3 data products.

In addition to this report, the CCVS projects also delivered a specific report on the Copernicus Cal/Val Solution [RD28] providing recommendations to the Cal/Val means for each earth observation techniques of the Copernicus constellation and on each surface. This report emphasises the better validation status for the larger targets (large lakes and the largest rivers) which is mainly driven by a better representativeness and data quality of the reference data sets that can be used compared to the smaller water bodies as illustrated in Figure 4.

WSH (Water Surface Height)	Ref. Data Representativeness				Ref. Data quality				Validation Method				Validation results				Overall
	In-situ	Inter-sat	Models	Alternative process	In-situ	Inter-sat	Models	Alternative process	In-situ	Inter-sat	Models	Alternative process	In-situ	Inter-sat	Models	Alternative process	global score
WSH (Lakes and large rivers)	Good	Good	Poor	Good	Excellent	Excellent	Poor	Excellent	Good	Good	Poor	Good	Excellent	Excellent	Poor	Excellent	Good
WSH (Small lakes and rivers)	Poor	Poor	Poor	Poor	Excellent	Good	Poor	Good	Good	Good	Poor	Good	Poor	Poor	Poor	Poor	Poor

Figure 4: Product validation status for Inland Water from the CCVS project

The report notes that smaller rivers are likely to present larger slopes, making the altimetric water level estimates comparisons to nearby in situ gauges more sensitive to biases induced by the height (slope times distance) in between the virtual station and in situ measurement. Smaller water bodies also have a lower contribution in terms of the backscattered signal compared to surrounding echogenic targets (other water bodies, sand benches, anthropic reflective surfaces), making their contribution more difficult to disentangle in the altimetric waveforms, results are much more 'environmental' dependant for small water targets, leading to lower representativeness.

The strategy for the operational FRM provision for inland water proposed in this document account for these remarks and propose relevant solutions to tackle the slope/topography issues, the lower representativeness of small water bodies and the issues with the distance between the virtual station and the in situ measurement.

2.3. Strategy principle

In this chapter we define the strategy to provide operational Fiducial Reference Measurement (FRM) over inland water bodies. This strategy has been designed to be routinely and operationally performed with affordable costs and meeting the FRM needs in terms of quality, uncertainty, and traceability.

As described in [RD7], the approach in the frame of this project is focused on Cal/Val super sites, completed using existing networks over various surfaces. The objective is to define reference Cal/Val sites called Cal/Val super sites based on the following criteria:

- hydrological characteristics
- one or several Sentinel-3A and/or Sentinel-3B virtual stations in a restricted area (Sentinel-6 or other flying altimeter missions can be accounted for)
- geometry (orientation) of water body with respect to the Sentinel-3 track(s)
- potential crossovers with other missions (especially with Sentinel-6, but also CryoSat, SWOT, Icesat-2)
- presence of historical and/or existing in-situ data in the area
- ease of installation of additional sensors

These reference sites are used as golden sites and have been equipped with all instruments needed to ensure operational FRM provision over a long-term period with affordable cost effort and accounting for the water surface topography and the specific properties of the area. With this approach, a limited number of Cal/Val super sites have been selected mainly in Europe (Maroni site in French Guyana has also been instrumented to build and federate the international user community, and other sites implemented for SWOT mission have inherited from [RD7] recommendations). These sites will allow an in-depth understanding of inland water altimetry measurements, analyse the quality of the Sentinel-3 inland operational water products, the one delivered by Copernicus Land Service and contribute to the improvement of the ground segment processing. We propose a set of Cal/Val super-sites to perform in-depth analysis on a representative sample of different river and lake cases. For rivers, the proposed super sites allow to analyse rivers of different widths, with simple (canals) and complex topography (Garonne, Po), slow or dynamic temporal variations and with different measurement geometries (from perpendicular to parallel). For Cal/Val activities it is important to have different sites with different configurations (both in terms of hydrological properties and crossing geometries with Sentinel-3 orbits), in this context we do not recommend having a limited number of Cal/Val super sites. The more we have, the better it is for Cal/Val purposes. So, any new Cal/Val super site will be welcome. In order to have a representative set of cases, a number of 40 to 50 super sites would be relevant. However, and as done over the ocean surfaces, we strongly recommend pursuing the efforts on the set of super sites instrumented during this St3TART project as Cal/Val approaches require a much longer duration than the current St3TART phase.

We also propose to complete this strategy with opportunity sites based on existing in-situ networks combined with activities to make existing measurements meet the FRM requirements when possible. The resulting FRM provisioning strategy scheme is presented in Figure 5.

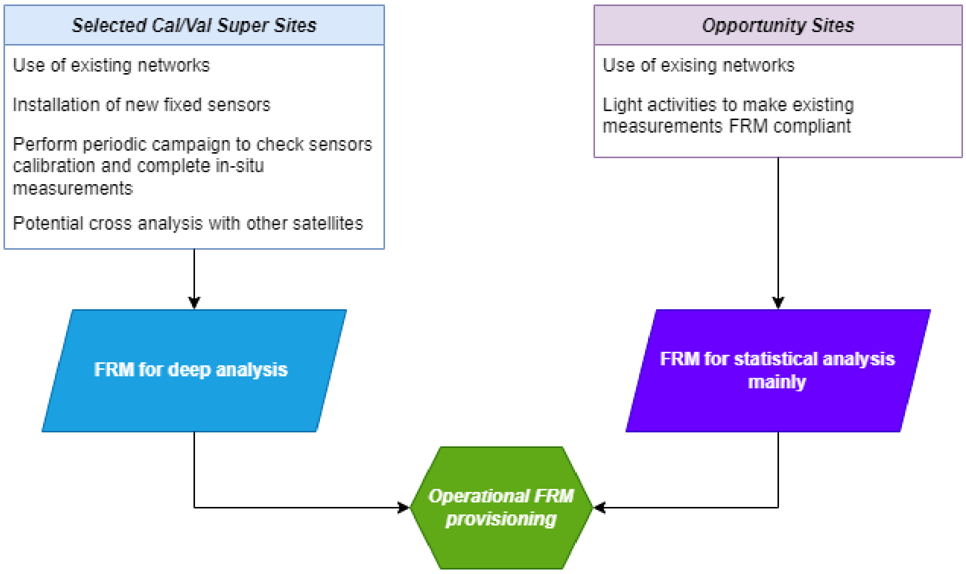


Figure 5: FRM provisioning strategy.

Of course, statistical analysis will be performed on Cal/Val Super Sites in addition to the deep analysis.

This roadmap for Cal/Val of Sentinel-3 measurements over hydrological areas is in line with the Sentinel-3 MRTD [RD13]. With the proposed strategy, Cal/Val activities will be able to evaluate the Sentinel-3 performances according to the requirement S3-MR-180 from [RD13], which states that "Sentinel-3 shall provide measurements of River and Lake Heights (RLH) for large rivers, their tributaries and lakes to at least the quality of the RA-2 on ENVISAT", and also the requirement S3-MR-1200: "Sentinel-3 shall provide River and Lake Hydrology (RLH) and River and Lake Altimetry (RLA, containing individual retracked radar echo waveforms) products shall be delivered to the hydrological services in a timely and operational manner."

In this context, the roadmap presented in this document will allow to ensure the operational provision of Fiducial Reference Measurement to perform Cal/Val activities of Sentinel-3 (among other missions), and to fulfil the mission requirements concerning river and lake heights. The provision of FRM for inland waters will also serve scientific and hydrological interest and ensure performance evaluation of future Algorithm Processing Baseline evolutions.

2.4. Sensors

Based on the sensor review made in [RD7], almost all sensor types analysed are precise enough to be used for operational FRM provisioning, as long as regular calibration activities are performed, at least twice a year. But all sensors are not equivalent in terms of ease of installation, of operationality and of data transmission and remote-control capability.

In the frame of the St3TART project and depending on the site configuration and infrastructure, we have made use of the following sensors:

- vorteX-io micro-stations
- pressure sensors
- radar sensors
- Cyclopée acoustic altimeter
- CalNaGeo towed GNSS carpet
- vorteX-io drone-embedded LiDAR

Moreover, it has been demonstrated in the [RD7] that surface roughness and the actual satellite overflight track are strong contributors to the uncertainty of altimetry measurements over inland water. It is also important to evaluate the performance and the behaviour of the different in-situ sensors with respect to surface roughness evolution.

In order to meet FRM requirements we have performed sensor performance analysis (see [RD7]) in a test basin to evaluate the capability and the absolute uncertainty of the sensors that will be used in the project. The objective of this experiment was to establish the relation between the measured height and the actual height as a function of the surface roughness variation. The test basin of Marseille-Luminy (LASIF) has been used for this experiment. The Marseille-Luminy wind wave facility is known by the scientific community working in the fields of air-sea interactions and marine technologies as a unique installation owing to its large dimensions and the exceptional quality of the air and water flows respectively generated in the wind tunnel and the water tank (at least in France). The facility is extensively used for measuring air-water surface fluxes in realistic sea conditions (momentum, energy, mass and gas exchanges), investigating small-scale wind wave roughness and the associated acoustic and electromagnetic wave backscattering at the water surface and more recently, characterising the aerodynamic and hydrodynamic responses of marine structures as floating wind turbines.

2.5. Cal/Val super sites

In [RD7], we have demonstrated that each site is different depending on its geography, water surface topography, geometry with the satellite track and the hydrological context. It is thus impossible to propose the provision of the same operational FRM equipment for all Sentinel-3A or Sentinel-3B virtual stations covering an inland water body or an estuary. All sites need to be selected with a lot of care and the instrumentation to be installed is site dependent. Indeed, this is also a lesson learnt from the Ocean super sites installed by the different teams: one needs to account for the local constraints, and if there is some generic process to follow, the selection of sensors needs to be adapted to the site characteristics.

Following the strategy described in chapter 2.1, Cal/Val super sites are identified and selected within different inland water bodies, where all instruments needed to tackle the different uncertainty contributors to the water surface height measurement have been installed. The objective was to have a set of reference sites providing operational FRM with long-term support and with different hydrological characteristics. Cal/Val super sites must ensure the validation of the Sentinel-3 data products over inland waters on this long-term basis, including future missions such as Sentinel-3C and, of course, Sentinel-6 virtual station. Those sites will also be important for the validation of future missions like CRISTAL and could be valuable for old missions like ENVISAT. Indeed, it has been demonstrated several times in the past that R&D activities and new reference data provide a new perspective on the behaviour and issues of past missions.

These Cal/Val super sites are clearly mandatory for rivers, where the impact of the surrounding environment, the water topography of the river and its variation in time must be analysed and measured precisely to meet FRM requirements and provide uncertainty and traceability required by FRM. Indeed, it has been demonstrated by Sandwell & Smith (2014) [RD9] that the Point Of Closest Approach (POCA) moves from the nadir position depending on the slope of the water surface, knowing that the slope values are not constant along rivers. Thus, the height error due to this slope effect can reach several centimetres as shown in Figure 6 and Figure 7. In addition, as the position of the satellite track moves from cycle to cycle within +/- 1 km [RD7] of the reference ground track, the POCA will move from cycle to cycle according to the position of the track and the variation in the slope/landform of the river. It is thus mandatory to have regular measurements of this slope or to build a slope variation chart to properly know where the actual satellite measurement is located. This slope measurements must be provided as a product of FRM measurements over rivers.

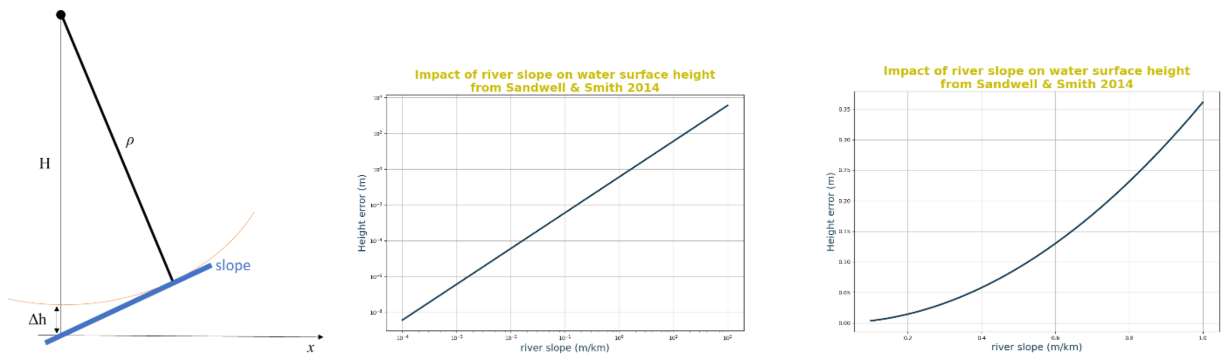


Figure 6: Geometry of the altimetry measurements over a river slope (left), impact of river slope on water surface height measured by satellite altimetry computed from Sandwell & Smith (2014) [RD9] (centre) and zoom on some specific river slope values (right).

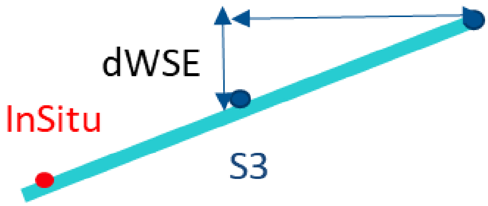


Figure 7: Scheme of the river slope impact for Cal/Val over river with a permanent in-situ sensor

For rivers, we selected the following Cal/Val super sites in the frame of the project:

- Garonne river near Marmande in Southern France which is a very interesting site representative of medium-width rivers (about 150 m) with a strong height dynamic and a challenging water topography. This site is also of interest because of the multiple crossovers of 2 Sentinel-3A ground tracks along a 15 km-long segment in addition to a Sentinel-6 crossover and the fact that Sentinel-6-MF is quite parallel to the river over about 15 km. This river mostly has an orientation South-East → North-West
- Canal du Midi near Trèbes and Pompignan in the South of France which is an ideal case for Sentinel-3 measurements. This site is a thin, flat and controlled canal crossed by a Sentinel-3A track perpendicular. With these conditions, we will be able to measure the performance of the Radar altimeter and potentially get an uncertainty driven by the instrument uncertainty. This site has been also selected because a bridge is located just below the Sentinel-3 ground track, which facilitates the installation of an in-situ sensor.
- Rhine river in France near Strasbourg and in several places in Germany: it is a large river with a strong hydraulic control, which leads to a succession of flat-water surface segments with a very small slope, separated by jumps of different altitudes. Jumps can reach a height of several metres. This river is mainly oriented South → North.
- Po river in Italy: selected for its East-West geometry allowing multiple high-angle crossings, with Sentinel-3 tracks. The main river width ranges from 200 m to nearly 500 m. In light of its geometrical characteristics and the amount of available hydrological observations, the Po River represents an ideal test case for the validation of altimetry satellite missions.
- Tiber river in Italy: selected for its North-South geometry and its width of the order of 50-80 m only.

Concerning lakes and reservoirs, super sites are important to measure geoid errors over big lakes, to account for the actual differences between the altimeter measurement performed in the middle of the lakes and that obtained from the sensors at the lake shore and the roughness impacts. The work performed in TD-1 showed that surface roughness can have a strong impact on the altimeter signal. As surface roughness over lakes is mainly due to the wind stress, a wind speed measurement must be provided. This wind sensor might not be enough as the wind generates local stress effects on the water surfaces that are highly dependent on the surrounding topography and wind intensity. To perform an actual measurement of the surface roughness during the satellite overflight, an automatic vehicle (UAV) could be deployed. For lakes, we propose to rely more systematically on existing in-situ networks. Indeed, it has been shown in [RD7] that several existing in-situ sensor networks over lakes allow easy access to their near real-time measurements, and are well maintained and of good quality, notably in Switzerland, Norway, USA and Denmark (among many other places). We therefore propose to use such existing networks and to perform periodic campaigns for regular calibrations with moving sensors such as drone-embedded LiDAR or towed GNSS carpet in order to improve the knowledge of the local geoid and to check the calibration of existing in-situ sensors. The roughness impact must be monitored through wind speed measurements that must be collected around lakes.

In this context, the selected Cal/Val super site over lakes is limited to two sites, Issykkul Lake, where a lot of analysis has been conducted for many years and where a lot of activities will be conducted in the framework of the SWOT Cal/Val phase and Montbel Lake (South of France). In addition to these super sites, and as demonstrated in [RD7], the use of the opportunity site is particularly reliable on lakes and will therefore be widely used.

For Lakes, the selected Cal/Val super site are the following:

- The Issykkul Lake which has been studied for many years and is well known and well instrumented.
- The Montbel Lake
- All lake targets with a reliable, well-maintained sensor from the existing networks with a Sentinel-3 ground track crossing the lake.

2.6. Opportunity Cal/Val sites

To complement super sites and increase the number of FRM sites over inland water, with limited costs, it is interesting to take advantage of existing in-situ networks when the measurement stations are located less than 150 m from the satellite reference ground track (as a first guess), but this distance can be increased if the local slope is small or well characterized. Indeed, thanks to the different national in-situ networks, which are mostly public and free to use, the opportunity must be analysed to consider as an opportunity Cal/Val site for operational FRM provision a site where in-situ measurements are:

- located below a Sentinel-3 track (or Sentinel-6) at less than 150 m from the satellite reference ground track. Some sites can be selected at a higher distance if they have small or well-characterized slope (e.g., for relatively small lakes that can be assumed to be flat).
- easy to access: data shall be easy to collect in order to meet the reliable timeliness requirement
- data available within a 28-day latency
- traceable: clear information on sensors, data processing, calibration and positioning must be available to meet the requirements of the metrological approach.
- well georeferenced: georeferencing shall be assessed with external data (IceSat-2, other satellites measurements, in-situ means, bibliography, etc.).
- not requiring strong effort to make FRM compliant, following requirements written in [RD7].

If all the conditions listed above are met, the site can be used and selected as an opportunity Cal/Val site for operational FRM provision. Depending on the site characteristics, additional instrumentation or calibration as listed below can be installed at moderate cost:

- installing an automatic station (vorteX-io micro-station)
- and/or installing a citizen science system (plain rule installed, citizens provide water height by reading the rule)
- and/or performing a precise georeferencing of the existing in-situ sensor.

It is important to note that the selection of opportunity sites will be done on a case-by-case basis due to the different problems that are encountered as soon as existing in-situ systems are considered. Indeed, a lot of systems installed by national or local authorities are dedicated to flood risk monitoring and are not well georeferenced (or not georeferenced at all) and they only provide a relative water surface height. The sensors dedicated to flood risk are not calibrated on a regular basis either, which is an important issue to meet FRM requirements. Some of the existing networks are also not well maintained which is a strong problem for long term usage. Finally, there are existing in-situ stations that have been installed by local companies (energy suppliers, water companies, etc.) and for which it will be very difficult, if not impossible, to access and retrieve the data regularly.

2.7. Federate the hydrological community

2.7.1. Collaboration with the European Environment Agency

The European Environment Agency (EEA, https://www.eea.europa.eu/en) is an agency of the European Union that delivers knowledge and data to support Europe's environment and climate goals. The core tasks of the EEA are defined in the founding EU regulation and include:

- supporting policy development and key global processes;
- offering analytical expertise;
- providing and maintaining an efficient reporting infrastructure for national and international data flows.

In collaboration with the partner network, Eionet, EEA informs decision-makers and the public about the state of Europe’s environment, climate change and wider sustainability issues.

The EEA is currently working in the H2020 COINS project (Copernicus In Situ, https://insitu.copernicus.eu/) with different activity. A meeting with the team in charge of the hydrology activities has been performed in order to exchange on the potential collaboration between this project, EEA and the needs of the St3TART project. The COINS project aims to:

- **Determine the state of play:** maintain an overview of Copernicus' in situ data requirements, use, and challenges.
- **Provide access to data:** establish, maintain, and improve operational provision of selected in situ data in accordance with the Entrusted Entities' needs.
- **Engage with data providers:** engage and create partnership and other agreements with in situ data providers, networks, and organisations to improve in situ data access and use conditions in accordance with Copernicus' needs.
- **Engage with data providers:** engage and create partnership and other agreements with in situ data providers, networks, and organisations to improve in situ data access and use conditions in accordance with Copernicus' needs.

It has been decided during the meeting that the COINS project and EEA will facilitate the access to in situ data from the different national providers contributing to EEA and Eionet (The European Environment Information and Observation Network). In this context, contacting EEA and the COINS project to access to new public national networks is warmly recommended for the need of the opportunity sites over Europe.

In this framework, a report has been released on the hydrological data requirements for Copernicus. The report was prepared by a group of experts for the European Environment Agency, coordinating the Copernicus Programme In Situ Component [RD26]. In situ data are essential for the validation of satellite datasets and are routinely used in the production and validation of Copernicus products. This report identifies the data needs for the development of hydrological outputs from the Copernicus programme, assesses gaps in the availability of these data, and proposes coordination mechanisms to improve the availability. Addressed are the measurements of river levels and flows, lake levels, river water quality, lake water quality (including temperature), and soil moisture.

Several Copernicus services use hydrological data collected by national regulatory agencies with some measurements undertaken only within research activities. The European Flood Awareness System (EFAS) delivered by the Copernicus Emergency Management Service (CEMS) extensively uses river flows and levels data. CEMS maintains a dedicated data centre to collate and quality control these data from national agencies. The Copernicus In Situ Component coordinated by the EEA is working with the EFAS hydrological data collection centre to improve the licensing under which this data is acquired and to help this data be of wider use across the Copernicus Services within the development of other products.

The Copernicus Land Monitoring Service (CLMS) river level products will particularly benefit from these hydrological data as the availability of near real time river levels is limited at both European and global scales. CLMS and the Copernicus Marine Environment Monitoring Service (CMEMS) are both working on satellite products to improve understanding of coastal zones and will need river flow and water quality data. The report suggests that the national agencies should adapt their statutory monitoring strategies to acquire the in situ data needed for satellite monitoring.

The St3TART project and the roadmap proposed here is perfectly in line with these recommendations.

2.7.2. Open call system

It is important to underline that this ESA initiative is mainly addressed to European countries and aims at federating the hydrological community to contribute to the provision of FRM following this roadmap.

In this context, an open call system (Announcement of Opportunity call) should be defined based on this roadmap for implementing new opportunity site. It is important to note that a long time is required to evaluate and qualify a site (validate the instrument choices, the location of each instrument, analyse the seasonal effects, etc). It is therefore important to account for the long-term operational needs in these open calls. These open calls shall account for the opportunity site requirements listed in section 2.6.

2.8. Classification of Cal/Val sites

As mentioned above, each Cal/Val sites is different from one to another due to the hydrological characteristics, the surrounding terrain, the crossing geometry with Sentinel-3 ground tacks or the ease of installing instrumentation in the field. The objective of this document is to provide a roadmap for performing the operational provision of Fiducial Reference Measurements (FRM) to support operational Cal/Val activities.

In this context, it is important to identify categories between Cal/Val sites depending on:

- Hydrological properties of the inland water body
- Crossing geometry with Sentinel-3 ground tracks.
- Location of the in-situ sensors

The chosen convention is to classify Cal/Val sites depending on the complexity to provide/compute FRM for Sentinel-3 Cal/Val activities accounting for the 3 points mentioned above.

Following this convention, 4 classes have been defined: Complexity Level 0 (CL0), Complexity Level 1 (CL1), Complexity Level 2 (CL2) and Complexity Level 3 (CL3), from the “simplest” case to the “most complex”. It is important to note that for sites where the river and the satellite track are collinear, the Complexity Level can change from a CL0 to a CL1, CL2 or CL3 depending on the hydrological properties of the inland water body and with the increasing distance between the actual satellite measurement and the reference in-situ station.

It is worth to mention that this classification is valid for Cal/Val super sites for both rivers and lakes. The strategy for opportunity sites is to only consider Complexity Level 0 to ease the automatic processing for the statistical analysis.

2.8.1. Complexity Level 0 sites

Complexity Level 0 sites correspond to the simplest case for the FRM provision.

Characteristics:

- The in-situ sensor is installed/located just under the Sentinel-3 ground track (inside the orbit excursion area which corresponds to a +/- 1 km around the Sentinel-3 reference ground track)
- Water bodies with no or very moderate slope (small lakes, reservoirs, canals…)

Additional data:

- No external data is needed.

The FRM measurement:

- Ideally, the in-situ measurement must be synchronised with the satellite pass (in-situ measurement performed at the same time as the satellite measurement). If not possible, a workaround can be found by interpolating between 2 in-situ measurements at the time of the satellite overflight.
- The FRM measurement corresponds to the measurement of the in-situ sensor (IS), levelled with respect to the reference ellipsoid: $\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t)}$
- The FRM uncertainty corresponds to the sensor uncertainty.

2.8.2. Complexity Level 1 sites

Complexity Level 1 sites correspond to Cal/Val sites where in-situ sensors are not located under the Sentinel-3 ground track (distance between the in-situ sensor and the actual satellite ground track longer than 1 km), with a steady water surface of the water body and no variation in time of the slope of the water body (like a canal or the effect of the geoid over a lake).

Characteristics:

- The in-situ sensor is not installed under the Sentinel-3 ground track (distance between the in-situ sensor and the actual Sentinel-3 ground track > 500m)
- The water body topography is not dynamic, and the slope or river profile is not evolving with the water level. Example: a canal with a linear controlled slope or the geoid effect over a lake.

Additional data:

- The slope of the water body must be measured by a moving sensor or, if possible, ICESAT-2, or 2 in-situ sensors in case of a canal

The FRM measurement:

- Ideally, the in-situ measurement must be synchronised with the satellite pass (in-situ measurement performed at the same time as the satellite measurement). If not possible, a workaround can be found by interpolating between 2 in-situ measurements at the time of the satellite overflight.
- The FRM measurement corresponds to the measurement of the in-situ sensor (IS), levelled with respect to the reference ellipsoid and corrected from the slope effect: $WSH_{FRM}(t) = WSH_{IS}(t) + Slope$
- The FRM uncertainty corresponds to the in-situ sensor uncertainty combined with the slope measurement uncertainty.

2.8.3. Complexity Level 2 sites

Complexity Level 2 sites correspond to Cal/Val sites where in-situ sensors are not located under the Sentinel-3 ground track (distance between the in-situ sensor and the actual satellite ground track longer than 1 km), with a dynamic water surface of the water body but no variation of the slope whatever the water level.

Characteristics:

- The in-situ sensor is not installed under the Sentinel-3 ground track (distance between the in-situ sensor and the actual Sentinel-3 ground track > 500m)
- The water body topography is dynamic, a propagation time must be accounted for between the position of the in-situ sensor the position of the Sentinel-3 ground track
- The slope (geoid effect on a lake) or river profile is not evolving with the water level

Additional data:

- The slope of the water body must be measured by a moving sensor or, if possible, ICESAT-2, or 2 in-situ sensors in case of a canal
- A second in-situ sensor is mandatory to measure the propagation time. The Sentinel-3 virtual station must be located between the 2 in-situ sensors

The FRM measurement:

- The propagation time δt must be accounted for when considering the measurement from the in-situ sensor. This propagation time must be computed using the 2 in-situ sensors located on both side of the Sentinel-3 virtual station
- The slope of the water body must be accounted for between the position of the in-situ sensor and the Sentinel-3 virtual station
- The FRM measurement corresponds to the measurement of the in-situ sensor at the time of the satellite overflight t plus the propagation time δt corrected from the slope effect: $WSH_{FRM}(t) = WSH_{IS}(t + \delta t) + Slope$
- The FRM uncertainty corresponds to the combination of the in-situ sensor uncertainty, the slope measurement uncertainty (moving sensor) and the propagation time uncertainty

2.8.4. Complexity Level 3 sites

Complexity Level 3 sites correspond to Cal/Val sites where in-situ sensors are not located under the Sentinel-3 ground track (distance between the in-situ sensor and the actual satellite ground track longer than 1 km), with a dynamic water surface of the water body and a complex topography, the slope evolving with the water level.

Characteristics:

- The in-situ sensor is not installed under the Sentinel-3 ground track (distance between the in-situ sensor and the actual Sentinel-3 ground track > 500m)
- The water body topography is dynamic, a propagation time must be accounted for between the position of the in-situ sensor the position of the Sentinel-3 ground track
- The water topography is complex and evolving with the water level

Additional data:

- The slope of the water body must be measured at 3 different water levels (low, medium, and high) by a moving sensor
- A second in-situ sensor is mandatory to measure the propagation time. The Sentinel-3 virtual station must be located between the 2 in-situ sensors

The FRM measurement:

- The propagation time δt must be accounted for when considering the measurement from the in-situ sensor. This propagation time must be computed using the 2 in-situ sensors located on both side of the Sentinel-3 virtual station
- The slope of the water body must be accounted for between the position of the in-situ sensor and the Sentinel-3 virtual station
- The slope should be interpolated between the 3 mobile sensor profiles at the water level value corresponding to the time of the Sentinel-3 overflight, assuming that a certain water level value was assigned to each of the 3 profiles at the time t_c of their respective campaign.
- The FRM measurement corresponds to the measurement of the in-situ sensor at the time of the satellite overflight t plus the propagation time δt corrected from the slope effect interpolated at the corresponding water level: $\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t + \delta t) + Slope(WSH_{IS}(t_c))}$
- The FRM uncertainty corresponds to the combination of the in-situ sensor uncertainty, the slope measurement uncertainty (moving sensor), the propagation time uncertainty, and the slope interpolation uncertainty.

2.8.5. Summary of the classification

Table 1 summarises the site classification, the characteristics of each class and the associated FRM equation. The Cal/Val super sites selected in the framework of the St3TART project have been distributed among the different classes in the last row. The details can be found in the Section 3 of [RD32].

For all sites, it is worth to mention that surrounding water bodies can disturb the satellite measurements and can then reduce to 0 the interest of such Cal/Val sites. Depending on the objective of the Cal/Val site, it is important to consider the importance of the surrounding water bodies. If the site is dedicated to analysing the performance of Sentinel-3 measurements over a specific inland water target, then it is important to select sites without any surrounding water bodies present in the SRAL footprint.

	CL0	CL1	CL2	CL3
Characteristics	- Located under satellite ground track - No slope correction - No propagation time correction	-Not necessarily located under satellite ground track - No propagation time correction - Slope correction but not dependent on the water height	- Not necessarily located under satellite ground track - Propagation time correction - Slope correction but not dependent on the water height	- Not necessarily located under satellite ground track - Propagation time correction - Slope correction evolving with the water height
FRM equation	$\boldsymbol{WSH_{IS}(t)}$	$\boldsymbol{WSH_{IS}(t) + Slope}$	$\boldsymbol{WSH_{IS}(t + \delta t) + Slope}$	$\boldsymbol{WSH_{IS}(t + \delta t) + Slope}$
Cal/Val sites	Trèbes, Pompignan, Po River (Isola Pescaroli for S3B), Tiber River (Santa Lucia), German Rhine (Sankt-Sebastien, Mannheim, Oestrich-Winkel, Schierstein)	Chalampé, Esslingen-am-Neckar, Honfleur	French part of the Rhine River (Fesseinheim, Ottmarsheim)	Garonne River, Po River, Tiber River

Table 1: Summary of the site classification

Finally, no particular recommendation can be made on the distribution of sites between the different classes. These classes have been defined to provide a calculation of the different FRMs depending on the context but do not prejudge the quality of a site. It is quite possible that a Class 4 site will provide better results than a Class 0 site. We simply recommend here to have a distribution between the different classes consistent with reality to have metrics representative of the satellite performances.

2.8.6. Harmonisation between sites

The strategy proposed in this document is also a guarantee of the harmonisation in the FRM products delivered operationally. In this context, the consistency of FRM operationally delivered is ensured by the protocols, procedures and standard FRM processing described in this document. The FRM provision must be ensured by the methods and processing defined in this document and by a uniform FRM processing that has been published on a GitHub (st3start/fidji_mockup.ipynb at main · jcpoisson/st3tart · GitHub) in order to align the different cases. This processing must be maintained and improved in the future to account for all new site characteristics. Associated uncertainty provided to each FRM and computed following the metrological approach of chapter 6 is also mandatory for each site.

3. Cal/Val super sites over rivers

3.1. Introduction on the rationale

For river super sites, the recommended solution combines permanent sensors and periodic campaigns. The solution is described by the scheme in Figure 8. The objective is to equip the site with automatic and connected stations as close as possible to the reference ground track or covering the actual track variations. The number of stations will depend on the river topography, its variation, and the available location and infrastructure on site to install automatic stations. If the river topography is as simple as a small, linear slope in case of a segment with channel-like behaviour, two automatic stations are enough, one at each end of the segment. In this case, it is not mandatory to install stations within this +/- 1 km area even if it should be better. Also, if the slope is particularly low (which is for example the case for most of the main rivers like Congo, Amazon, or Rhine Channel art) the +/- 1 km constraint might be relaxed.

In case of a more complex river topography, the installation of more than 2 micro-stations is recommended, if possible within the +/- 1 km area around the reference ground track. A set of stations equally distributed and separated by a few tenths of metres would be ideal, but it is rarely possible to find infrastructure permitting this. Different sensor technologies can be used depending on the site constraints (available infrastructure, location for sensor installation, topography, risk areas, etc). On the other hand, an automatic data transmission system is required to automatically transmit data to the datahub within the 1-2-day latency required for the Cal/Val activities (required by MPC). A health monitoring system of the station is also mandatory to monitor the proper functioning of the station and to ensure the operationality.

To monitor permanent sensors, we propose to install a citizen science system (which has a very low impact in terms of cost) near the location of permanent sensors, mostly for lakes but also for some rivers. The citizen science measurements permit to detect potential drifts or failures and allow to raise awareness about hydrological issues among the citizens. Citizen science has already demonstrated its added value in the provision of high-precision measurements but also in terms of very low costs. However, citizen science cannot be used on an operational basis due to high seasonality and site dependency as explained in [RD7].

If available, existing sensors can be used on super sites, but the quality and the compliance of the existing sensors must be checked with respect to FRM standards. A GNSS calibration can be performed on the existing sensor to properly reference the precise position and the measurement of the sensor. It is also necessary to ensure that the data is accessible on a regular basis and that the time taken to make the data available is compatible with the expected latency for operational Cal/Val activities.

In addition to these permanent sensors, periodic campaigns must be performed. These campaigns will serve 2 different purposes:

- calibration campaigns
- river topography measurement campaigns

The first purpose is to ensure the calibration of all sensors present on the super sites. It is important to check the quality of the measurements and to ensure that all measurements are comparable in the same reference system. The second purpose, as important as the first one, is to provide a measurement of the water surface topography and its evolution over time, between all sensors and the satellite virtual station locations. Indeed, [RD7] has demonstrated the importance of knowing the river topography and its variation throughout the year. As the satellite ground track moves within 1 km from cycle to cycle, it is not possible to provide the height of the water surface below the satellite track at each cycle with permanent sensors, unless a sensor is installed for example every 100 metres, which is not really possible nor cost effective. It is thus mandatory to measure the water topography along the river between the permanent sensors and the satellite ground tracks. In this context, periodic campaigns must be performed at different water stages using one of the moving sensors reviewed in [RD7]. The choice of one sensor rather than another will be done depending on the site constraints. In this project we choose to use the vorteX-io drone-embedded LiDAR altimeter, the towed GNSS carpet or Cyclopée depending on the Cal/Val sites. The objective is to build different river topography profiles at different water heights and to provide these sets of profiles to users to correct the measurement of the permanent sensor from the height difference between the actual ground track and the permanent sensors due to the distance between them.

All sensor measurements (both permanent and periodic) must be calibrated with a high-precision GNSS positioning system to provide measurements with a common reference system and comparable to the satellite measurements. In this context, it is mandatory to provide all height measurements with respect to the WGS84 reference ellipsoid as the one used by the Sentinel-3 missions. It is also mandatory to provide the associated uncertainty for each measurement.

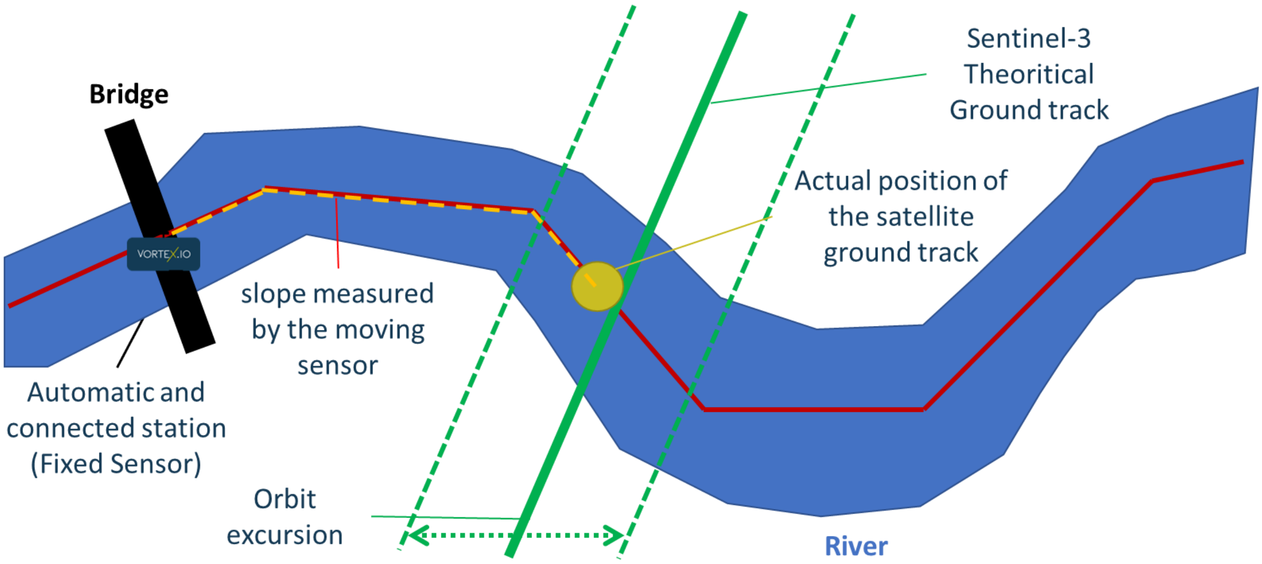


Figure 8: Scheme of Cal/Val super site instrumentation over a river

3.2. Strategy for the computation of FRM over rivers

In this chapter we propose a generic strategy to compute Fiducial Reference Measurements over rivers. Of course, depending on the site characteristics (distance between the actual nadir track position and the closest in-situ station, slope / topography of the river), the recipe can be simplified.

3.2.1. Prerequisites

Before starting to compute the FRM, it is important to first compute the following variables:

- The curvilinear abscissa to get the distance between two in-situ stations, but also to be able to compute the distance between the actual nadir track position and the closest in-situ station
- Topography or slope measurements along this curvilinear abscissa. If the river slope is linear (for example when the river segment is controlled by a lock or if the water body is a canal), then the slope is simply computed using in-situ stations by a simple difference between 2 simultaneous in-situ water surface height performed by the 2 in-situ stations and by dividing the height difference by the distance between the 2 stations.

The number of slope/topography measurements needed depends on the actual dynamics of the river. If the water level of the river changes rapidly and significantly over time, several height profiles of the river at different water levels are needed to interpolate the topography using the water level measured at the time the satellite flies over the river.

It is important to note that if the river topography is measured by mobile sensors (drone, CalNaGeo, Cyclopée, boat, etc.), then it is mandatory to correct the measurements of the mobile sensors for the water level evolution observed during the measurement of the mobile sensors. Indeed, the objective here is to measure an "instantaneous topography" which should not be impacted by the temporal variation of the water level during the campaign. To do so, in-situ stations present in the area are used to correct the time evolution of the water surface height from the moving sensor measurements during the campaign.

3.2.2. Computation of the FRM

The computation of the FRM is described in Figure 9. The objective of this strategy is to provide the in-situ water surface height at the actual nadir track position station and to ensure that the in-situ measurement has measured the same water particle as the satellite. A mockup of this processing developed in python is also provided into a github in a jupyter notebook. The github can be freely accessed here: https://github.com/jcpoisson/st3tart/blob/main/frm_mockup/fidji_mockup.ipynb. An Algorithm Baseline Theoretical Document (ATBD) will be also provided at the end of the project.

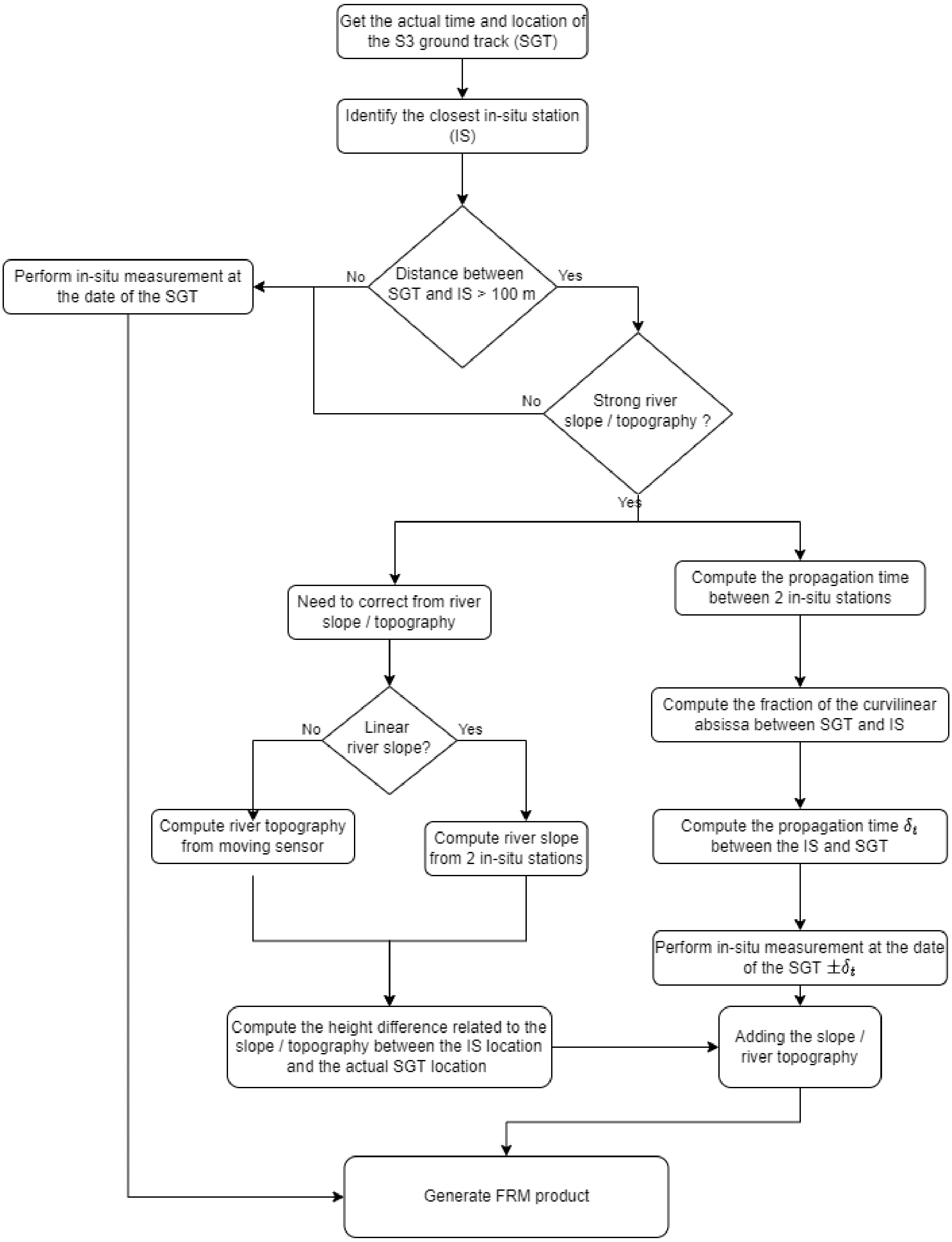


Figure 9: Scheme detailing the strategy to compute FRM over rivers

The processing described here corresponds to Figure 8 and the different steps are detailed below:

1. Based on the prerequisites, the first action consists in computing the exact position of the actual nadir track position along the curvilinear abscissa.
2. Then, the closest in-situ station (automatic and connected stations is preferred) is identified. The distance between the closest in-situ station and the actual nadir track position is computed.
3. If the actual nadir track position is located at a distance < 100 m from the in-situ station, or if the river slope is almost flat, then the FRM corresponds to the measurements of the in-situ station performed at the exact time of the satellite measurement. If a vorteX-io micro-station is used, simply set up the station so that the in-situ measurement is taken at the precise date of the satellite pass. If the in-situ station is not a micro-station, then the in-situ measurement must be interpolated to the exact time of the satellite pass. The FRM is directly generated from this measurement (jump directly to point #7).
4. If the actual nadir track position is located at a distance > 100 m from the closest in-situ station and the river slope topography is not "flat", then the river slope / topography must be accounted for.
   If the river is linear, then the river slope computed in 3.2.1 is simply multiplied by the curvilinear distance between the closest in-situ station and the actual satellite measurement.
   If the river topography is not linear, then the topography measured beforehand using moving sensor campaigns is used. If the river is dynamic (i.e. with a river slope evolving with the water level), the river topography must be interpolated between two different river topographies measured at 2 different water surface heights, using the actual water surface height measurement from the closest in-situ station. If the river slope is not dynamic, the river topography measurement is directly used. Then, the river slope is accounted for by computing the height difference on the river topography between the position of the actual nadir track position and position of the closest in-situ station. The resulting value corresponds to the topography correction.
5. Due to the distance between the closest in-situ station and the actual satellite measurement, the water propagation time must be accounted for (see Halicki et al. 2022 [RD14]) when considering the in-situ station measurement to compute the FRM. Indeed, as illustrated in Figure 10, the objective is to measure the same water particle with the in-situ station as that measured by the satellite. In this framework, the propagation time δ_{ts} must be accounted for and the in-situ measurement must be considered at the exact date of the satellite measurement +/- δ_{ts} (+ if the in-situ station is located downstream of the satellite measurement, - if the in-situ station is located upstream).
   This propagation time is computed using 2 in-situ stations (1 upstream and 1 downstream of the actual nadir track position) and using their measurements performed during few days before the date of the actual satellite measurement:
   a. First the propagation time δ_{ti} between the 2 in-situ stations. To do so, 5 days of water surface height measurements from both stations are considered. From these two timeseries, we apply a Nelder-Mead algorithm to minimize a least square criterion to find the propagation time δ_{ti} between the two stations. This computation can be performed using anomaly instead of using their absolute measurements (the average value is subtracted to both stations). If the propagation time is properly estimated with a high degree of confidence (minimizing the least square criterion and with a maximum correlation value), the two time series are synchronized when the δ_{ti} is applied to one station as shown in Figure 11, where the δ_{ti} has been computed and applied to the micro-station called "le-mas-d-agenais_1" in dashed blue and compared to the "marmande_1" station over the Garonne River.
   b. Then the propagation time δ_{ts} is computed from a fraction of the δ_{ti}. This fraction is simply the ratio between the two curvilinear distances, assuming that the velocity is constant.
6. The FRM measurements is then computed from the closest in-situ station measurement taken at t+ δ_{ti} and corrected from the slope / topography correction computed in point #4. If a vorteX-io micro-station is used, simply set up the station so that the in-situ measurement is taken at the precise date of the satellite pass + δ_{ti}. If the in-situ station is not a micro-station, then the in-situ measurement must be interpolated at the exact time of the satellite pass + δ_{ti}.
7. The FRM product is then generated in NetCDF format.

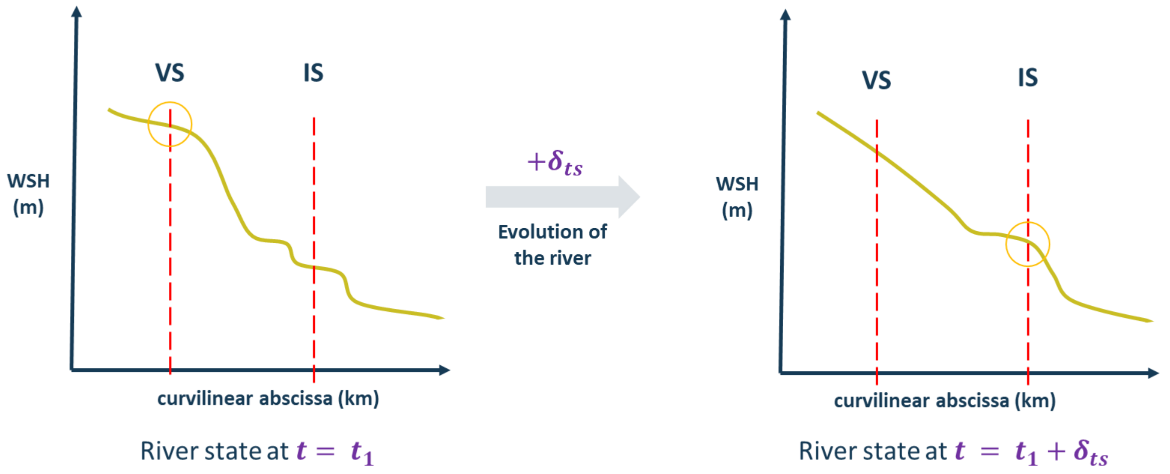


Figure 10: Diagram explaining the propagation time issue

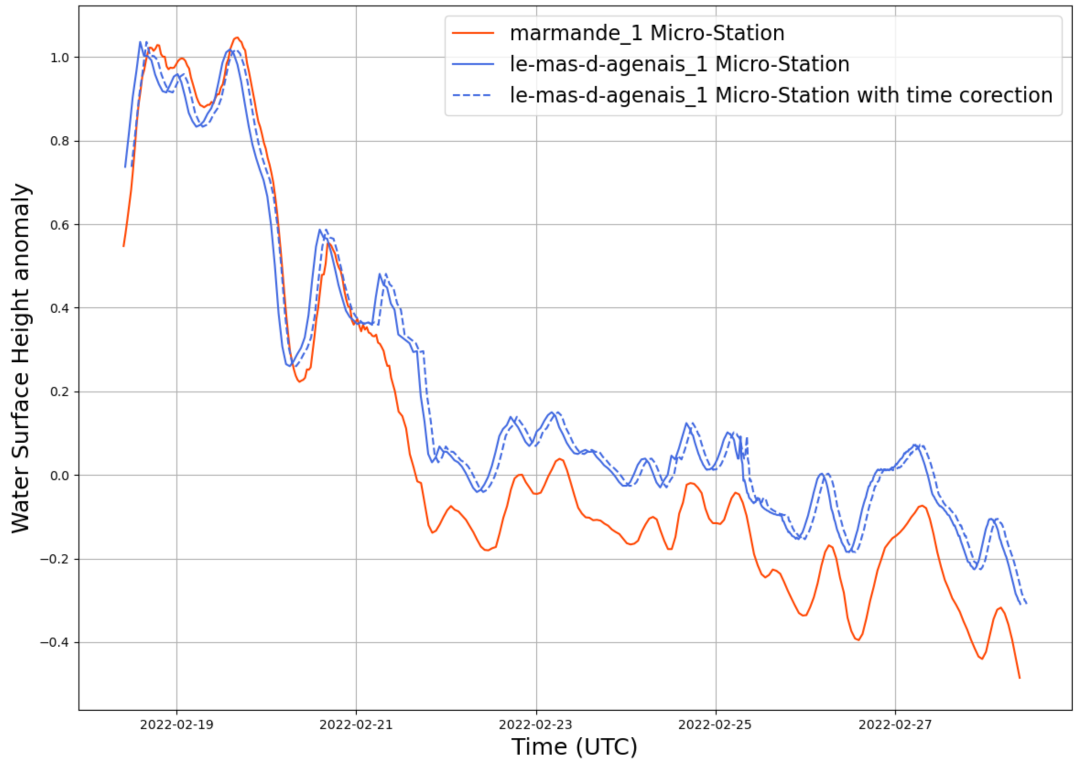


Figure 11: Comparison of WSH anomaly between "le-mas-d-agenais_1" (in blue) and "marmande_1" (in red) over the Garonne river before (solid) and after (dashed) the correction of the propagation time

To summarize, here is the equation corresponding to the FRM measurement:

$$WSH_{FRM}(t) = WSH_{IS}(t + \delta_{ts}) + \left(\Delta WSH_{slope} - Corr_{evo\_tempo}\right)$$

with $\Delta WSH_{slope} = WSH_{moving\_sensor\_at\_SGT} - WSH_{moving\_sensor\_at\_IS}$

and where $WSH_{moving\_sensor\_at\_IS}$ corresponds to the moving sensor measurement next to the in-situ sensor and

$\boldsymbol{WSH_{moving\_sensor\_at\_SGT}}$ to the moving sensor measurement at the actual position of the satellite ground track. $\boldsymbol{Corr_{evo\_tempo}}$ corresponds to the correction related to the spatial and temporal evolution that we apply on the moving sensor measurements to correct the water level evolution of the river during the campaign time.

It is important to mention that the ideal FRM scenario would be to use an autonomous drone solution to be able to deploy the drone at the exact time and location of the satellite pass (no matter what time of the day or night). But unfortunately, this solution is not available at this time, and that is the reason why we propose to combine different sensors to provide the best FRM possible.

Finally, the approach we propose here is based on water height interpolation, but we assume to obtain better performances when working with river discharge instead. Of course, this assumption and the associated activities (this method requires bathymetry measurements) can be explored in the future but are not included into the St3TART project.

3.3. Computing FRM over the selected Cal/Val super sites

3.3.1. Super-sites description

For the selected super-sites description, refer to Sections 2.1 of TD-01 [RD3].

3.3.2. Particular cases

3.3.2.1. Case of Estuaries

The estuaries are a highly dynamical regions where river and ocean water masses meet, resulting in a mix of various processes, such as river flows, ocean tides, storm surges and local sea level variations. The interactions between the ocean flow and the river flow can produce distortions in the high-frequency variations of the water level measured in estuarian regions, especially in areas strongly influenced by ocean tides. The implementation of Cal/Val sites for the SWOT mission in the estuaries, have highlighted the need for very high time sampling in the in-situ measurements to be able to catch these quick variations. Furthermore, in these regions, the presence of wetting/drying areas can affect the waveforms satellite altimetry observations. The satellite measurements should be analysed to check the impact of such areas in the comparison with in-situ observations.

In the energetic environments of estuaries, the comparison between altimetry and in situ water heights shall dynamically consider the water height difference between the locations of the two measurements (in the equation below). To catch the water level dynamics over a few kilometres, the moving sensors (as GPS carpet, drones and airborne LiDAR) are too slow, very expensive and can be limited by weather conditions. In this context, models become essential to remove the aliased high-frequency dynamical signals due to the ocean tide and storm surge from the satellite altimetry measurements over estuarian regions, in order to obtain high-quality data.

$$Diff_WSH(t,C) = WSH_alti(t,C) - WSH_gauge(t,G) + \Delta WSH[river, tides, surge](t,C,G)$$

The implementation of hydrodynamic models in estuaries such as the Gironde, the Seine and the Elbe (performed by LEGOS, University of Rouen and NOVELTIS) has highlighted that the complexity of the interactions between river flow and ocean dynamics in those estuaries requires to locally constrain the model with tidal observations in order to obtain errors that are small enough to be useful for the altimetry Cal/Val activities for missions like SWOT and Sentinel-3. Moreover, to produce hydrodynamic simulations, the gauge time series used as upstream boundary condition needs to be as clean and complete as possible (no noise and no interruptions of measurements), which is difficult to ensure when the instrument is maintained by an external institute that is not necessarily aware of such operational use of the data. Because of all these reasons, the installation of Cal/Val sites in estuaries is key to integrate the observations into the already existing network of tide gauges in the estuary to be used in the model assimilation scheme in future Cal/Val activities.

3.3.2.2. Case of icy rivers

The icy rivers are specific regions with a strong seasonality due to the presence of ice during the winter period. This particular case has not been addressed in this project but is of interest because of the location of these sites. Indeed, icy rivers are mainly located at high latitudes with a high sampling of the Sentinel-3 orbit. But it also represents a high complexity due to the presence of ice during the winter period which effects and impacts must be carefully analysed on the Sentinel-3 measurements before defining a strategy for an operational FRM production. This particular topic should be the subject of a dedicated study phase. To do so, a flag indicating the presence of ice, or the percentage of the iced river surface will be useful to perform this study. In-situ images of the river at each measurement can be a solution to set up this “in-situ” ice flag. Investigating opportunity sites can be dangerous if this ice flag is not provided.

4. Cal/Val super sites on lakes

4.1. Introduction on the rationale

For lake super sites, the recommended solution combines permanent sensors and periodic campaigns. The solution is described by the scheme in Figure 12. The recommended solution relies on the use of existing in-situ networks. The existing sensor data must be checked with respect to FRM standards. A GNSS calibration must be performed on the existing sensor to properly reference the precise position and the measurements of the sensor. It is also necessary to ensure that the data is accessible on a regular basis and that the time taken to make the data available is compatible with the expected latency for operational Cal/Val activities.

Existing sensors can be complemented with an automatic and connected station only if the installation of such a system is possible within the +/- 1km excursion area.

Periodic campaigns must be performed with moving sensors in order to measure the water surface height of the lake below the Sentinel-3 ground track. The objectives are double: first the periodic campaign will provide a calibration for all sensors present in the area, but the most important goal is to measure the mean lake profile in order to correct satellite measurements from local geoid errors. Indeed, [RD7] has shown the importance of geoid errors when comparing satellite data acquired over lakes to permanent in-situ sensors, knowing that geoid models are not accurate enough over big lakes, leading to errors of several tenths of centimetres. Any of the moving sensors described in [RD7] can be used for these periodic campaigns, the choice of sensor will be done depending on the ease of deployment on the field. In this project we choose to use the vorteX-io drone-embedded LiDAR altimeter and the towed GNSS carpet depending on the Cal/Val sites. Note that for Level 0 lakes (e.g., a small lake with negligible slope), campaigns to establish height profiles is not mandatory; a precisely calibrated gauge is sufficient.

Finally, it is important to retrieve wind speed measurements in the area at the time where the satellite observes the lake. The strong impact of water surface roughness on the radar altimeter echoes has also been demonstrated in [RD7]. In this context, data from local in-situ wind speed sensors must be collected and provided into the FRM products.

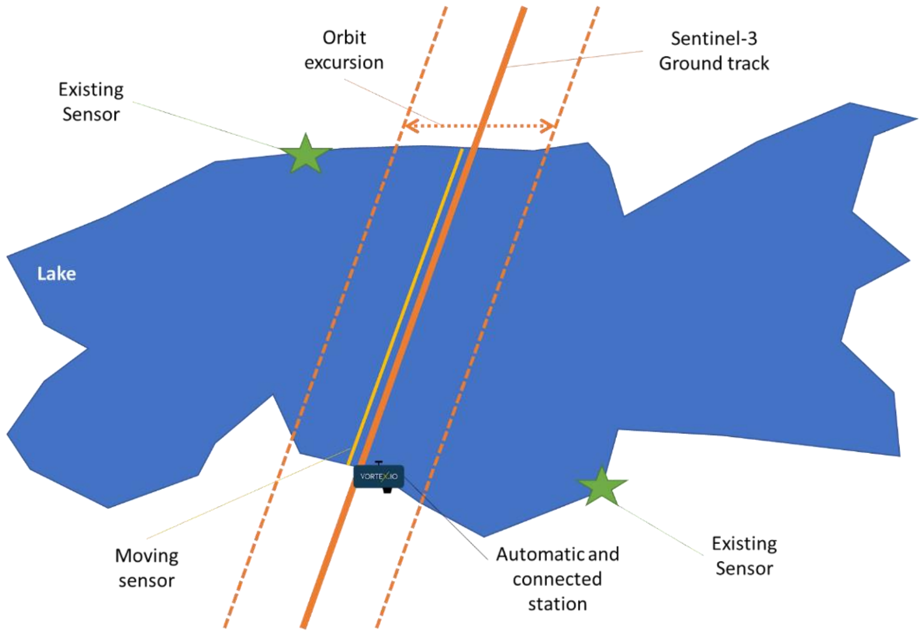


Figure 12: Scheme of Cal/Val “super site” instrumentation over a Lake

4.2. Strategy for the computation of FRM over Lakes

The strategy for lakes is based on the extensive use of existing gauge networks and the use of the Issykkul super site which has been instrumented for many years and on which operations are granted in the future as part of the SWOT Cal/Val phase. Also, this lake is located under the 1-day orbit of SWOT, and SWOT data will provide tremendous information on the actual roughness and water height variations. That SWOT information will be of key importance to address the most challenging features encountered over large lakes and related to the actual roughness variability.

4.3. Computing FRM over the selected Cal/Val sites

4.3.1. Issykkul Lake

Refer to Section 2.1.10 of TD-01 [RD3].

4.3.2. Montbel Lake

Refer to Section 2.1.11 of TD-01 [RD3].

4.3.3. Lakes with existing networks

In order to maximise the number of operational FRM provisions over lakes, an interesting means is to use existing sensors over different lakes managed by third-party organisations.

CNES has developed the 'LPP' system to process Sentinel-3 SAR data over lake surfaces. To ensure the validation of the performances of this new method, a large set of lakes with available in situ data has been selected. Based on the knowledge of the actual in situ data quality and trying to include various situations, the CNES team has selected the following set of lakes:

- USGS network in North America
- Ireland
- Russia
- Italy
- Brazil (Ceara)
- Madagascar

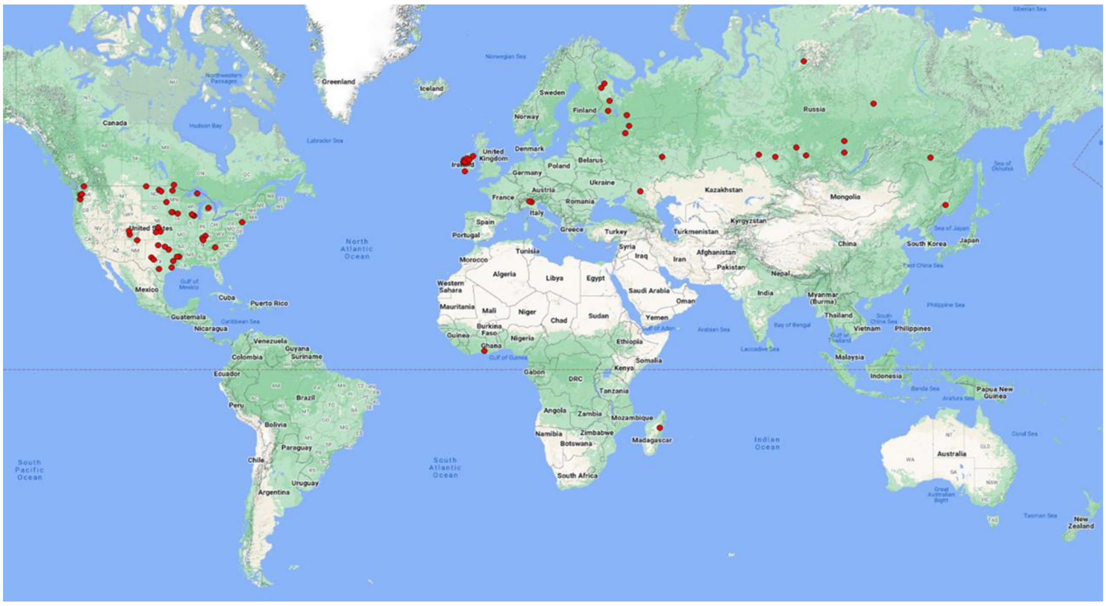


Figure 13: Map of lakes selected into the LPP database and equipped with reliable in-situ measurements

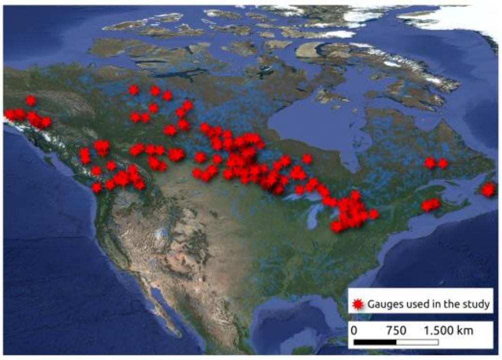
The data analysis over these lakes has not yet been completed, it will be performed in 2023 and a peer reviewed paper is planned. This will complement the one issued in 2020 by F. Boy et al.

4.3.4. Focus over US and Canadian lakes

Thanks to the study performed by Nielsen et al. in 2020 [RD25] a list of 76 US lakes has been analysed and selected. The gauge data from these lakes can be directly acquired on the USGS portal using the following link: https://waterdata.usgs.gov/nwis/sw.

The vertical reference of the gauge data is either relative or given in the American systems, The National Geodetic Vertical Datum of 1929 (NGVD29) and North American Vertical Datum of 1988 (NAVD 88).

The Canadian gauges data can be obtained from the Canadian government via the webpage https://wateroffice.ec.gc.ca/. The gauge level measurements are either provided with respect to a relative reference or the Canadian Geodetic Datum of 1928 - CGVD28. This datum is imprecise as an absolute reference and does therefore qualify as an FRM measurements without being referenced by GPS. However, the relative measurements are still of high quality and can be used to assess the relative variations of the S3 water levels in time. For the Canadian lakes 179 gauges were used to validate the Sentinel-3A /3B water level distributed over 133 lakes.



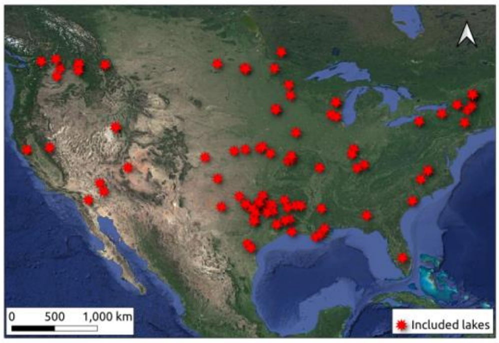


Figure 14: The location of the lakes/gauges us in the validation, left Canada, right, US

When validating the Sentinel-3 lake water level measurements several outside factors may influence the results, such as errors in the geoid model, the applied land-water mask, the presence of lake ice, distance between the gauge and the satellite track, a wrongly positioned range window.

A geoid is often used as a reference for altimetry-based lake water levels. In the official Sentinel-3 products, the EGM-2008 geoid model is provided. From ICESat-2 measurements it is easily shown that this model has errors over large lakes especially in mountainous areas. To minimise a potential error introduced by the geoid we create one time series per track.

In this analysis we apply the official Level-2 product “Enhanced measurements”, where elevations, based on the SAMOSA and OCOG retrackers, relative to EGM2008 are considered. To mask out the measurements related to the ground tracks that are within the lake area we intersect the location of the measurement with the lake mask “HydroLAKES” (Messager et al., 2016 [RD17]). For the Canadian lake evaluation, we used the Prior Lake database from the SWOT science team (Personal communication, Nicolas Picot). Additionally, for each observation we extract the occurrence value from the Global Surface Water product (Pekel et al., 2016 [RD18]). Water level times series are generated via the R-package “tsHydro” https://github.com/cavios/tshydro (Nielsen et al., 2015). A water level time series is generated for each combination of lake-track-retracker, this is to minimize the influence of potential geoid errors.

4.3.5. Focus over Swiss lakes

The FOEN (Federal Office for the Environment) operates and coordinates several water-related observation networks. It monitors the flow and quality of Switzerland's rivers and groundwater, as well as lake levels, by means of long-term observations at fixed stations and spot observations at temporary stations.

The network of the Hydrology Division of the Federal Office for the Environment concerning surface water currently provides data of 247 in-situ stations dedicated to water level. In addition to the water level, the network also measures the flow rate of rivers at 200 locations.

The in-situ station network is well maintained, and data can be easily and freely accessed through this link: https://www.hydrodaten.admin.ch/fr/messstationen_zustand.html.

All stations are correctly georeferenced but with respect to the local Swiss geoid. Figure 15 presents the location of the 247 stations dedicated to water level measurements.

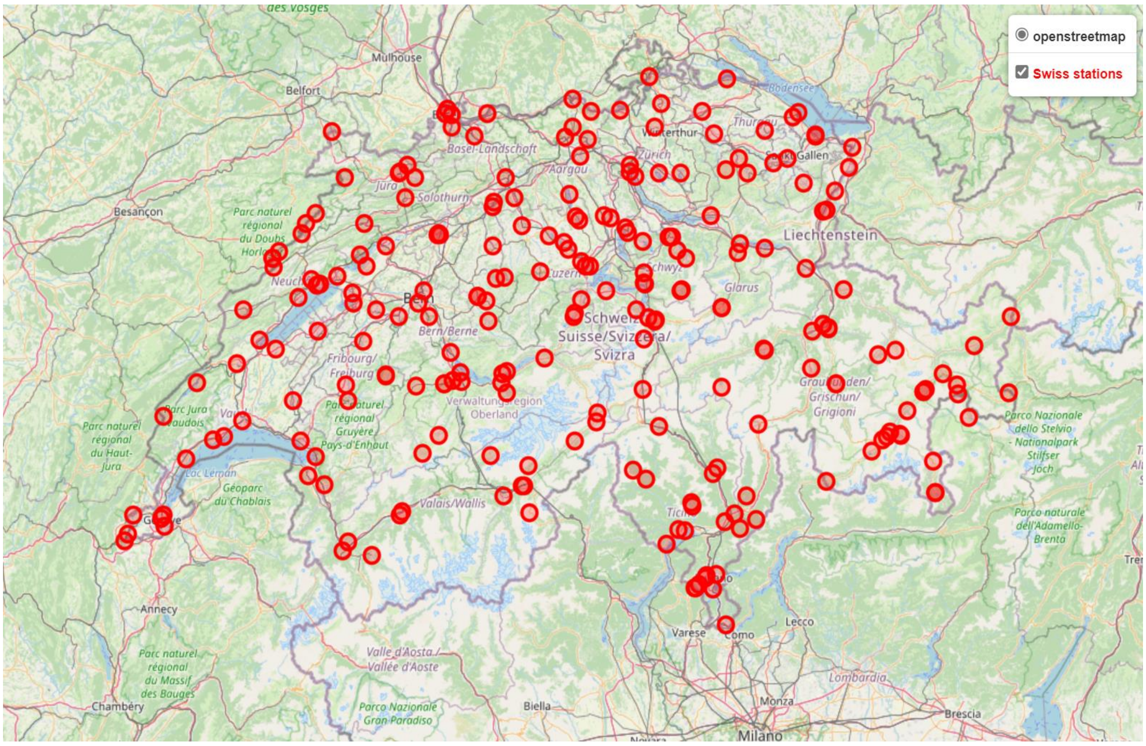


Figure 15: Map of Swiss in-situ stations dedicated to water level measurements

In [RD29] A full statistical analysis has been performed over Swiss lakes using the public national in-situ network described above. 14 lakes Swiss lakes with Sentinel-3A/B transects and equipped with in-situ sensors are available. They are shown on Figure 16.

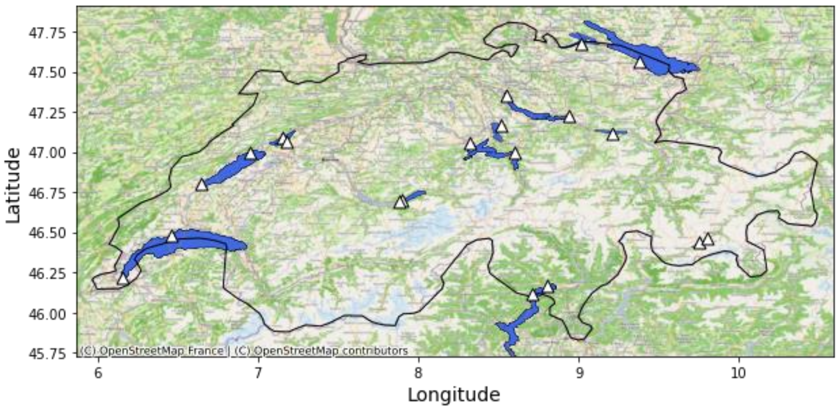


Figure 16: Map of the 14 Swiss lakes (blue areas) with S3A/B transects monitored by in-situ stations (white triangle)

The deep analysis performed on 3 different lakes (Geneva, Neuchatel and Bodensee) demonstrates the good quality of the in-situ sensors and the relevance of the statistical approach on these opportunity site with RMSE values between 10.7 cm to 28.7 cm.

5. Existing in-situ sensor networks for Opportunity Cal/Val sites

Please refer to TD-02 [RD4] for roadmap updates on opportunity sites.

6. Metrological uncertainty analysis for inland FRM

6.1. Various FRM approach

In this project, we have mainly focused on validations against in situ measurements of water level collected via fixed or moving sensors. Examples of a fixed FRM set up are tide gauges and vorteX.io micro-stations. In some cases, a fixed FRM set up is made up of more than a single instrument. For instance, when setting up a vorteX.io micro-station, we need a GNSS station and a tape measure to calculate the exact coordinates of the micro-station. Examples of moving sensors on the other hand are GNSS carpets and drone-board lidar altimeters. Similarly, a moving FRM set up may include more than a single instrument – e.g., a lidar ranger and a GNSS receiver onboard a drone. When it comes to designing a validation scenario, an FRM may consist of both moving and fixed sensors.

Due to time constraint, some of the validation techniques appearing on the comparison diagram (see [RD7]) were either not considered or only briefly touched upon. These include

- validation against water level measurements of other altimetry missions like Sentinel-6,
- validation against other physical quantities like discharge from in situ measurements or time series of surface water extent from satellite imagery, and
- internal validation of NRT measurements.

Notice that including the above-mentioned techniques in the comparison diagram (see [RD7]) does not guarantee the FRM compliancy of such methods. This will remain as an interesting research topic for future studies.

6.1.1. Case of micro-station and drone-board laser altimeter for rivers

6.1.1.1. FRM set up

Figure 17 shows one of the most representative FRM set ups in St3TART for validating Sentinel-3 data over rivers. This is a section of the river Marmande monitored by Sentinel-3A relative orbit #222. The highlighted section in cyan shows the trajectory of the drone campaign conducted by vorteX-io. The three vorteX-io micro-stations are represented as MS1, MS2, and MS3.

It is important to note that the case of the Marmande is categorized as a super site. This is due to having multiple satellite overpasses (from Sentine-3A and Sentinel-6 Michael Freilich) and site-related features which allows for installing and maintaining more than one micro-station as well as implementing multiple drone campaigns.

Ideally, the micro-stations would have been installed right under the satellite overpass to measure the same water level as that of the satellite altimeter at the same time. However, the satellite overpass is subject to deviations from the nominal track and that the optimum location for installing a micro-station is not necessarily located beneath the satellite track. These conditions are very generic and not specific to the Marmande site. Hence, our team has decided to install micro-stations at a reasonable distance from the altimetry virtual station and use river profiles acquired via drone campaigns to transfer the in situ measurements of water height to the right location.

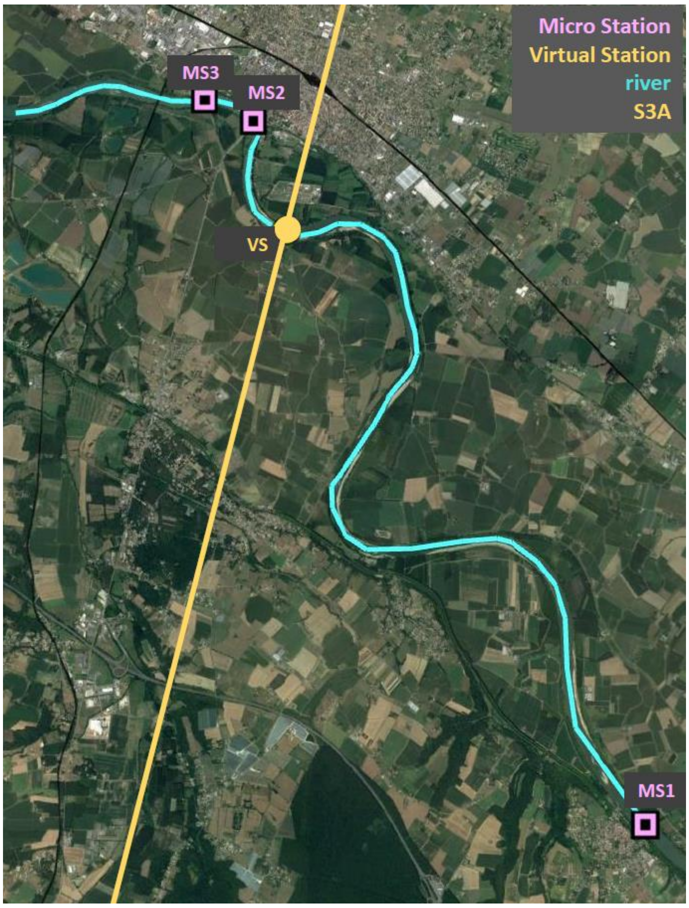


Figure 17. FRM set up using minimum of two micro-stations (MS1 & MS2) and a drone-board laser altimeter. Case of Marmande super site.

6.1.1.2. FRM Procedure

1. Drone campaign a is conducted.
2. The collected profile from drone campaign a is corrected for the fact that the whole profile is not acquired as a snapshot, i.e., the water flows as the campaign is being conducted.
   - We refer to this correction as C_{evo}.
3. Steps (1) and (2) are repeated for other drone campaigns.
   - For simplicity, we include only one more campaign in this example – campaign b (see Figure 22).
4. The water transfer time, Δt, between satellite virtual station and vorteX-io micro-station is derived.
   - Currently, Δt is considered as being a function of only the river length. In other words, we assume that the river centerline does not change in time and that the water flow is of a linear nature.
   - For simplicity, only the time transfer between VS and MS1 is used in the subsequent sections.
   - From hereafter, we denote location properties as a one-dimensional variable along the river centre line and starting from MS1 – i.e., location of MS1 is represented as $\ell_{\text{MS1}} = 0$ and location of VS is represented as ℓ_{VS}.
5. The micro-station read at time $t + \Delta t$ is recorded.
   - Notice that at time $t + \Delta t$ and location MS1, the micro-station is expected to sample the same water drop as it would have sampled at time t and location VS. This is of course only true under strong assumptions.

6. Based on the water level read at the micro-station, $h_{\mathrm{MS}}(t+\Delta t)$, the closest water profiles from the drone campaign are identified, Λ_{a} *and* Λ_{b}.
   - Assumptions are that we have at least two profiles, one, at higher and, one, at lower waters than that of the validation day. This is simply because we prefer to do an interpolation rather than extrapolation.
7. The FRM water level at time of flight $h_{\mathrm{VS}}^{\mathrm{FRM}}(t)$ is estimated (See the main measurement function in Figure 23).

6.1.1.3. FRM Uncertainties

The first step is to define the measurement functions. For clarity, we can define the measurement functions in a bottom-up order. The most basic measurement functions are those of the vorteX-io micro-station and that of the drone-board lidar altimeter.

- Height acquired at micro-station

Figure 18 shows the FRM set up for a micro-station under a bridge. The coordinates of the instrument are transferred from a GNSS receiver over the bridge to the micro-station under the bridge. It is assumed that the GNSS station can be set up exactly above the measurement center of the vorteX-io micro-station and that we can use a tape measure to derive this distance in a nadir manner and with a reasonably low measurement uncertainty.

Notice that the GNSS station is not permanent. Hence, the coordinates are defined at the beginning of the data collection period and calibrated later during the measurement period. The measurement function for any in situ height collected via a micro-station can therefore be described as

$$h_{\mathrm{MS}}(t') = h_{\mathrm{GNSS}}^{\mathrm{PPP}}(t') - \Delta h_{\mathrm{offset}} - \Delta h_{\mathrm{AD}}(t') + 0$$

$h_{\mathrm{MS}}(t')$ is the ellipsoidal height of water measured by the micro-station at time t'. $\Delta h_{\mathrm{offset}}$ represents the non-time-variant distance measured by the tape, and $\Delta h_{\mathrm{AD}}(t')$ describes the air draft measured by vorteX-io micro-station. To keep the equation in a generic form, we describe the GNSS height as a function of time.

It is important to notice that the micro-station and the GNSS station do not share the same sampling properties. Therefore, the discrete variable t' in the above equation, represents the air draft measurement and GNSS height after they have been resampled. This is clearly represented in the FRM uncertainty tree diagram (Figure 23), where the micro-station and GNSS stations have distinct original samplings shown by τ' and η'. Given that the GNSS station is not calibrated very often, the shared sampling of t' is expected to be a replica of τ' – the sampling of the lidar instrument on the micro-station.

The water level time series that is acquired at the micro-station can be described as

$$\boldsymbol{\Gamma}_{\mathbf{MS}} : \{\ldots, h_{\mathrm{MS}}(t'_{-1}), h_{\mathrm{MS}}(t'_0), h_{\mathrm{MS}}(t'_{+1}), \ldots\}.$$

The discrete indexing as shown above is selected to simplify the writing of equations in the subsequent stages. The current notation assumes that the 0 subscript represents the closest discrete sample to the desired point of evaluation.

- Estimated height for micro-station at time $t+\Delta t$

The micro-station has a sampling interval of 15 or 30 minutes, depending on the initial set up. We however are interested in the water level at micro-station at a very specific instant of time, $t+\Delta t$. It is possible to do linear, quadratic, cubic, or higher-level interpolation to estimate the height at time $t+\Delta t$ given the time series of $\boldsymbol{\Gamma}_{\mathbf{MS1}}$. As suggested by the uncertainty tree diagram (Figure 23), the linear interpolation reads

$$h_{\mathrm{MS1}}(t+\Delta t) = h_{\mathrm{MS1}}(t'_0) + \frac{h_{\mathrm{MS1}}(t'_{+1}) - h_{\mathrm{MS1}}(t'_0)}{t'_{+1} - t'_0}(t+\Delta t - t'_0) + 0.$$

t'_0 is the closest time sample at the micro-station to $t+\Delta t$ (see Figure 19).

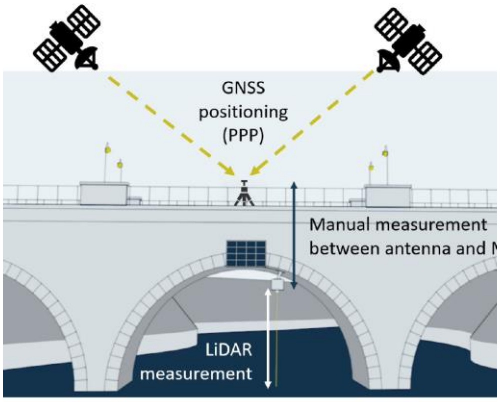


Figure 18. FRM set up for a vorteX-io micro-station

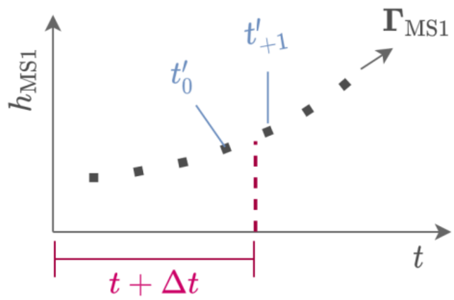


Figure 19. estimating micro-station height at continuous time $t + \Delta t$

- Height acquired by the drone

The next measurement function is that of the drone-board lidar altimeter (Figure 20). Interestingly, the measured water height can be represented with a very similar measurement function to that of a micro-station. Differences are in the Real Time Kinematic solution of GNSS, nature of the offset measurement, and the lidar instrument design. The measurement function, in this case, reads.

$$h_{\text{drone}}(t") = h_{\text{GNSS}}^{\text{RTK}}(t") - \Delta h_{\text{offset}} - \Delta h_{\text{AD}}(t") + 0.$$

Like the previous scenario, the original sampling of the GNSS height measurements and the air draft measured by the lidar instrument are not alike. Therefore, $t"$ describes the final sampling of a drone-board measurement after resampling both the GNSS measurements, $h_{\text{GNSS}}^{\text{RTL}}(\eta")$, and the air draft measurements, $\Delta h_{\text{AD}}(\tau")$. This is clearly demonstrated in the FRM uncertainty tree diagram (Figure 23).

It is important to notice that $t"$ may not be governed by only $\tau"$. Depending on the sampling features of both the GNSS system and the lidar instrument, different resampling solutions are conceivable.

The water level profile collected during the campaign drone is presented as

$$\boldsymbol{\Lambda}_{\textbf{drone}} : \{\dots, h_{\text{drone}}(t"_{-1}), h_{\text{drone}}(t"_0), h_{\text{drone}}(t"_{+1}), \dots\}.$$

- Estimated height from drone measurements at location ℓ

The trajectory of the drone flight deviates from the river centerline. Aside from this, the drone measures water level in a discrete manner. The FRM design however requires the water level exactly over the river centerline and at a specific point, ℓ_{VS} for instance. Therefore, we need to i) transfer the measured heights from the drone trajectory to the river centerline, and ii) estimate the height at the river centerline at any desired location ℓ. Figure 21 provides a schematic view of the situation. It is required that

1. all height measurements in the Λ: $\{\dots, h_{\text{drone}}(t''_{-1}), h_{\text{drone}}(t''_0), h_{\text{drone}}(t''_{+1}), \dots\}$ are corrected for the fact that the profile does not represent a snapshot of the river slope. This correction is noted as C_{evo}. See TD-1 [RD7],
2. every single sample is transferred to the closest point one the river centerline. As shown in Figure 21, the resampled measurements are not equidistant, and
3. the water level at point ℓ is estimated.

This can be done via two measurement functions. The first one projects the samples onto the river centerline and corrects for the evolution time,

$$h_{\text{drone}}(l) = h_{\text{drone}}(t") + C_{\text{evo}}(t") + 0.$$

After applying C_{evo}, the time variable $t"$ on the right-hand side of this equation disappears. This means that the collected profile is now a snapshot, and height measurements are accessible via the location samples l. The measurement function as presented here misses a term to correct for the slope along the projection line. By dismissing this term, we are imposing a very strong assumption to the $+0$ term: that the slope along all projection lines is negligible.

A second measurement function is now required to help estimate the water level at any desired location ℓ. Here we resolve the problem with a simple linear interpolation (See Figure 23):

$$\Lambda(\ell) = h_{\text{drone}}(\ell) = h_{\text{drone}}(l_0) + \frac{h_{\text{drone}}(l_{+1}) - h_{\text{drone}}(l_0)}{l_{+1} - l_0}(l - l_0) + 0$$

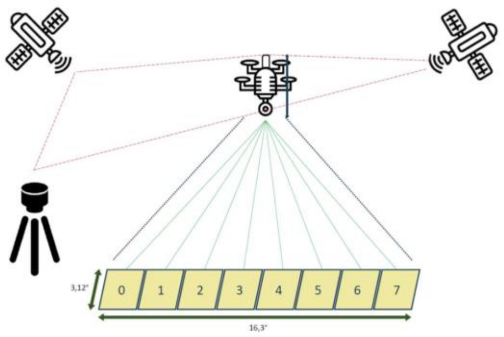


Figure 20. FRM set up of a drone board lidar altimeter

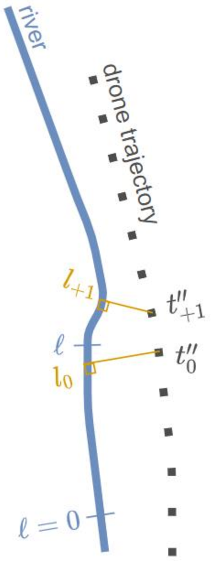


Figure 21. estimating drone-measured height at continuous location ℓ

- Main measurement function

The rationale behind the proposed FRM procedure in [RD7] is to read the water height at time $t + \Delta t$ and location MS1, as a representative of the height of the same water drop that the satellite measures at time t and location VS. Then we need to correct for the heigh difference between MS1 and VS due to river slope. This can be described as

$$h_{\text{VS}}^{\text{FRM}}(t) = h_{\text{MS1}}(t + \Delta t) + \Delta h_{\text{slope}} + 0$$

To derive Δh_{slope}, we need to know how this correction is derived. Figure 22 depicts the input information to the derivation of the slope correction. Δh_{slope} can be described as $h_{\text{VS}}(t) - h_{\text{MS1}}(t + \Delta t)$. So far, the only unknown is $h_{\text{VS}}(t)$. Given the height of the micro-station at time $t + \Delta t$, we can select two of the most representative water profiles. The next step would be to apply a linear interpolation to estimate the height at VS at time t. Same procedure can be mathematically described as

$$\Delta h_{\text{slope}} = \hat{h}_{\text{VS}}^{\text{drone + MS1}}(h_{\text{MS1}}(t + \Delta t), \boldsymbol{\Lambda}_{\text{a}}, \boldsymbol{\Lambda}_{\text{b}}) - h_{\text{MS1}}(t + \Delta t) + 0$$

A careful look into the two equations tells us that the FRM height at VS is nothing but an estimated height using both the lidar profiles and the micro-station time series. In fact, the ultimate measurement function can be described as

$$h_{\text{VS}}^{\text{FRM}}(t) = \hat{h}_{\text{VS}}^{\text{drone + MS1}}(h_{\text{MS1}}(t + \Delta t), \boldsymbol{\Lambda}_{\text{a}}, \boldsymbol{\Lambda}_{\text{b}}).$$

While more sophisticated solutions may exist, we define the actual measurement function to be a bilinear interpolator:

$$h_{\text{VS}}^{\text{FRM}}(t) = \Lambda_{\text{a}}(\ell_{\text{VS}}) + \frac{\Lambda_{\text{b}}(\ell_{\text{VS}}) - \Lambda_{\text{a}}(\ell_{\text{VS}})}{\Lambda_{\text{b}}(0) - \Lambda_{\text{a}}(0)}\left(h_{\text{MS1}}(t + \Delta t) - \Lambda_{\text{a}}(0)\right) + 0.$$

Notice Δt is derived from the micro-station time series.

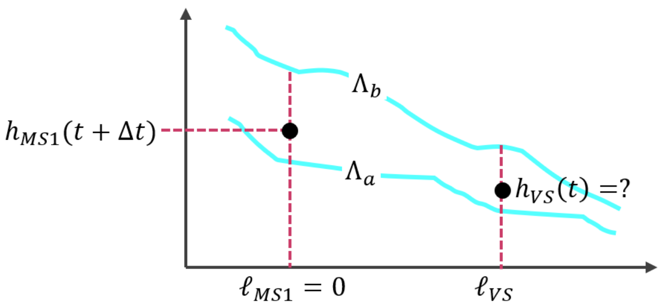


Figure 22. Deriving Δh_{slope} from lidar profiles and micro-station measurement

Remark: Towards the end of chapter 3 in [RD7], we proposed a scheme for the validation procedure which required a clear distinction between what is described as the instantaneous height measurement at the in-situ station, $h_{\mathrm{Inst.}}$, and what can be described as the altimetry equivalent height measurement for the virtual station, $h_{\text{Alt Equiv}}$. While any validation scenario can somehow be conceived as such, the measurement functions may not reflect such a clear step by step scheme. For instance, the proposed FRM procedure in [RD7] inherently resolves some of the concerns about data transfer in time and space without defining them as fully separate processing procedures. Therefore, we do not refer to the same terminologies in this section.

Figure 23 represents the uncertainty tree diagram for the suggested FRM procedure as discussed so far. The main measurement function is at the heart of the diagram. This is where the bilinear interpolation is implemented to estimate the FRM height at time $t + \Delta t$. Moving away from the center of the diagram, the main measurement function is broken down to measurement functions of lower level – hence, every single component of each measurement function is linked to an uncertainty term, $u()$, which is in turn derived from another measurement function. Double-line connections and envelopes are used to avoid repetition at different instances. For example, the uncertainty in quantification of $\Lambda_\mathrm{a}(0)$, $\Lambda_\mathrm{b}(0)$, $\Lambda_\mathrm{a}(\ell_{\mathrm{VS}})$, and $\Lambda_\mathrm{b}(\ell_{\mathrm{VS}})$ is shown with $u(\Lambda(\ell))$. This is due to the fact that the uncertainty in quantifying all of these components are expected to be calculated the same way.

The uncertainty break-down in Figure 23 covers only the high-level procedures for this specific FRM collection scenario. The six bold arrows facing outwards are used to emphasize that the break-down should further continue. For instance, in order to quantify $u(\Delta t)$, one shall analyze the uncertainties which are involved in the derivation of Δt.

As described in [RD7], after establishing the uncertainty tree diagrams, it is required that every identified effect is characterized via an effect table. This would allow for the estimation of uncertainty associated to the desired measurand in a fully metrological manner. All steps in this analysis requires to get properly documented.

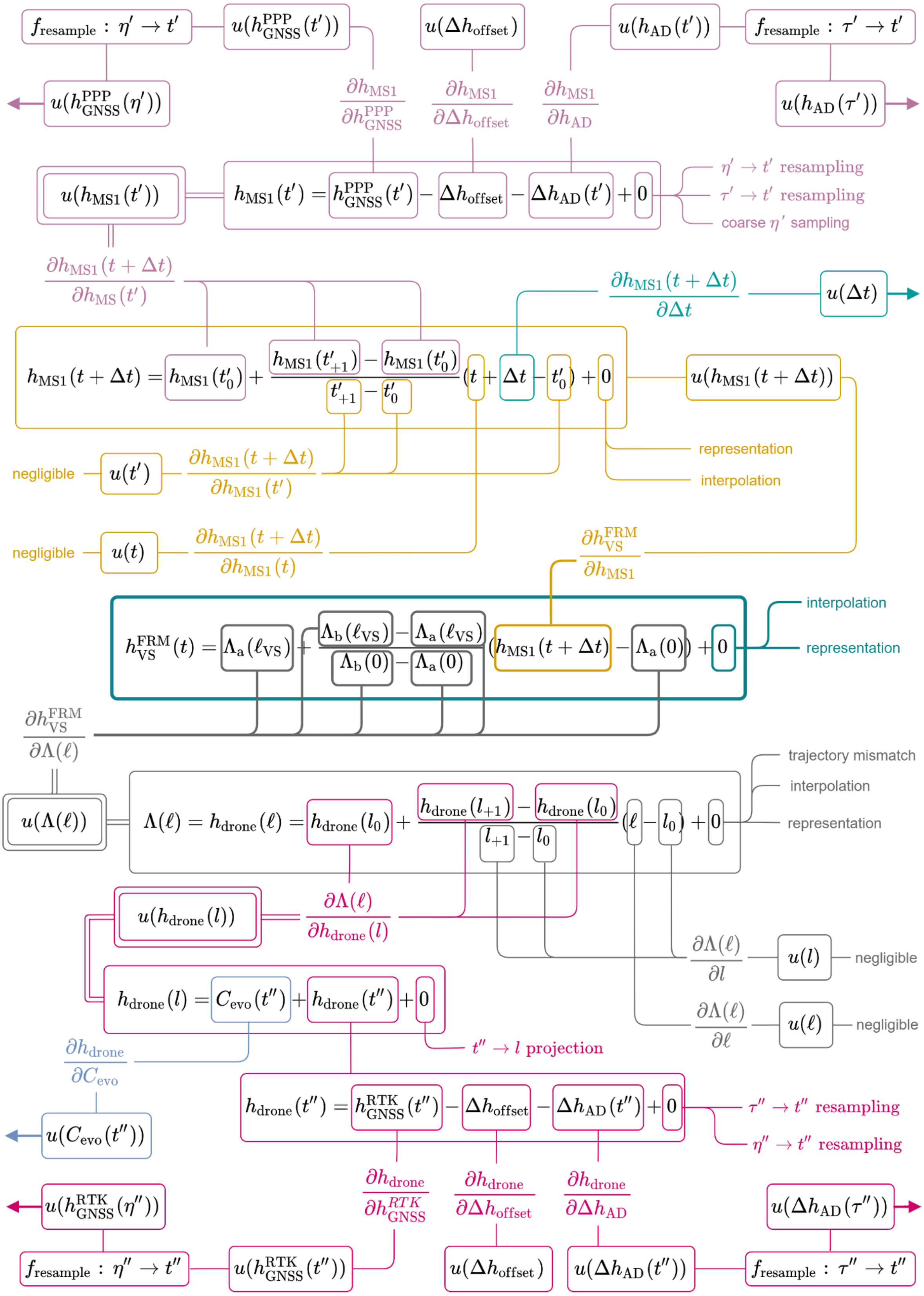


Figure 23. uncertainty tree diagram of the FRM procedures for the case of the Marmande River. Notice: the outward bold arrows show that there is a separate uncertainty tree diagram to be considered.

7. Conclusion

This document presents the Roadmap for S3 STM Land FRM operational provision for the "Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)" project which ran from 2021-2023. It details the different strategies, methods, processing, and sites selected and defined to ensure an operational provision of Fiducial Reference Measurements for the needs of the operational Cal/Val activities of the MPC over inland waters. This roadmap has been developed based on the requirements of the MPC to meet the MRD objectives and on the recommendation of the CCVS project. Additional discussions with the EEA helped to refine the roadmap to the document presented here.

With these bases and following the outcomes of the FRM Protocols and Procedure for S3 STM Inland Water Products, we have defined a strategy based on the development of a set of Cal/Val super sites combined with opportunity sites.

Cal/Val super sites consist in the installation of advanced in-situ instrumentation on a set of carefully selected sites in order to ensure the operationality of the FRM production, to serve as a reference in terms of FRM quality, and to allow the analysis, exploration, and better understanding of Sentinel-3 measurements in different configurations of inland waters. A set of 8 Cal/Val super sites (Canal du Midi, Garonne River, Po River, Tiber River, Issykkul Lake, Rhine River on both French and German sides, Seine estuary, Montbel Lake) have been detailed in this roadmap. These sites have been equipped and analysed during the project, and the conclusion for each site has demonstrated the validity of the approach.

Opportunity sites consist in the use of existing in-situ networks from different countries to increase the number of FRMs of opportunity on a large number of sites in order to provide statistical analysis of Sentinel-3 performance over inland waters. This document contains a non-exhaustive list of public networks that can be used as opportunity sites for the evaluation of the Sentinel-3 performances over inland waters.

The computation of FRM on each site has been detailed in a specific strategy and associated processing relying on the complexity level classification, offering a standard processing for each case. The strategy and the processing have been successfully implemented on almost all sites with very promising results.

All these activities have been supported by a metrological approach to derive the uncertainty tree diagram, allowing the computation of uncertainty for each class of the complexity level classification.

In conclusion, this document is a comprehensive work that serves as a foundation to operationally produce Fiducial Reference Measurements in St3TART-FO.